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RADIATION PROTECTION GUIDES AND DOSE ASSESSMENT

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RADIATION PROTECTION GUIDES AND DOSE ASSESSMENT

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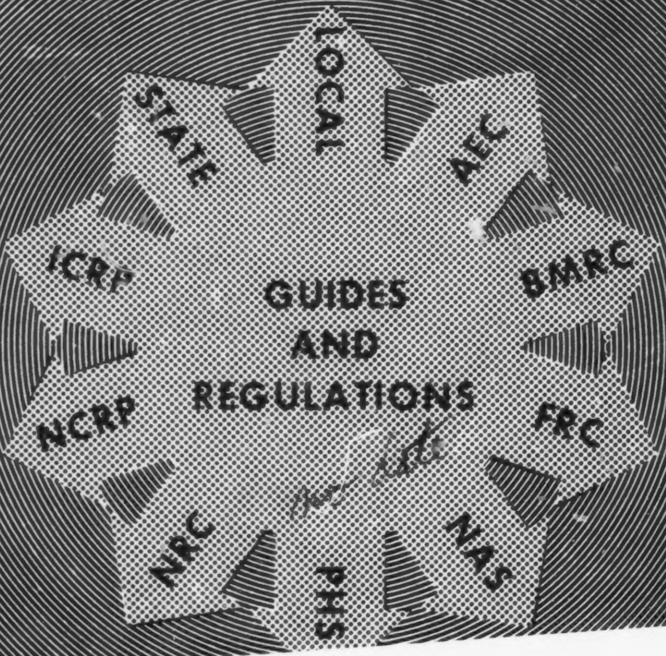
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RADIATION PROTECTION GUIDES AND DOSE ASSESSMENT
CESIUM-137 WHOLE BODY EXPOSURE AND OTHER RADIONUCLIDES
IN-CLASS PROBLEM SESSION

1. Establish the three ranges and Radiation Concentration Guides for Cesium-137 in milk for the general population. State all assumptions.

   Mass of infant 10 kilograms
   Mass of adult 70 kilograms
   Effective half life for infant 20 days
   Effective half life for adult 100 days
   $\sum EF(RBE)n = 0.59$
   fw = 1

2. Establish the three ranges and Radiation Concentration Guides for the oxide form of tritium (tritiated water) in tap water. State all assumptions.
   Effective half life 12 days
   $\sum EF(RBE)n = 0.010$
   fw = 1

CLASS PROBLEM

^{90}Sr

1) In the table below are the average monthly drinking water concentrations for first seven months of the year. In July , 1969, you are asked, as an expert, to evaluate this data, compare it with the FRC guides and to advise as to what action should be taken, if any. (For simplicity's sake, assume this is only nuclide intake of the population in any environmental media.

MONTH	AVERAGE CONCENTRATION of ^{90}Sr (pCi/ml)
Jan. 1969	3.0×10^{-2}
Feb. 1969	$4.0 \times 10^{+2}$
March 1969	$6.0 \times 10^{+3}$
April 1969	5.0×10^{-3}
May 1969	1.0×10^{-2}
June 1969	6.0×10^{-2}
July 1969	3.0×10^{-4}

CLASS PROBLEM - FRC: ^{131}I AND THE THYROID

Calculate the average daily intake of ^{135}I for an individual child in a population group.

$\Sigma \text{EF RBE} = 0.46$

$T_e = 0.28$

$f_w = 0.3$

CLASS PROBLEM
ENVIRONMENTAL STATISTICS II

1.

a) 36 water samples are collected and analyzed for ^{90}Sr. The MPC (W.B.) for ^{90}Sr is 4000 pCi/liter. From the 36 samples:

$\bar{x}$ = 3850 pCi/liter
s = 600

Test at the 5% level of significance, $H_o: \mu_o$ = 4000 pCi/liter

b) If the alternative hypothesis is: $H_A: {}_A = 3600$, what is the probability of making a type II error (β) accepting $H_o: \mu_o$ = 4000 when H_A is true.

c) What sample size should be selected to insure α = .05 and β = .20

2. Use the Mean Square Successive Difference Test to determine area homogeneity from the following data:

Sample #	Sample Value (pCi/l)
1	197
2	200
3	223
4	186
5	211
6	219
7	211
8	196
9	195
10	209

Note: For a sample size of 10, 95% of the time homogeneity will be indicated for D^2/s^2 values of 2.0 ± 0.94

STATISTICS I

CLASS PROBLEMS

1. a. Find the sample mean, variance and standard deviation of the following series of samples.

98
100
110
105
105
112
106
103
107
101

b. What is the 95% condifence interval?

2. A sample is counted for 100 minutes; the total count is 90,000 counts. Background is counted for 10 minutes; a count rate of 160 counts/min is observed. Report the net count rate at the 95% condifence interval.

NUCLEAR COUNTING STATISTICS

Class Problems

1. At the 68% confidence level what is the error in an observed count of 250,000 counts if the counting time is 100 minutes? At the same confidence level what is the error associated with the count rate?

2. In 10 minutes a sample shows a total count of 3000. A two minute background count is 24 counts. What is the reported value of the sample at the 95% confidence level?

3. What is the net sample count if the total count is 200 cpm ± 4 cpm at the 68% confidence level and at the 68% confidence level the background is 40 cpm ± 3 cpm.

BIO-ASSAY

Class Problems

Bioassay Problem #1

Tritium absorbed on a titanium foil is utilized as an ion source in the detection head of a gas chromatograph unit. It is suspected that a technician, in cleaning the foil, has ingested tritium. A 24-hour urine sample is obtained during the day following the suspected exposure and assayed for tritium. This bioassay reveals that 10 μCi of tritium is present in the 24-hour urine sample.

a. If it is assumed that the effective half-life of tritium is 12 days, what was the initial body burden?

b. Assuming uniform distribution in the body water, what is the dose commitment to the body water?

Given: Mass of critical organ (body water) = 4.3×10^4 gm
$\sum EF(RBE)_n = 0.01$.

Bioassay Problem #2

As health physicist at a research institute you have established a routine weekly urine sampling program for workers in a laboratory where ^{210}Po is used. One day the bioassay results show that a chemist excreted 30 pCi of ^{210}Po in his 24-hour urine sample. His previous urine sample contained no activity. You question the man, but find that he has no idea how or when the exposure might have occurred.

What dose commitment would you assign to the critical organ, the kidneys?

State your assumptions.

Given: $\sum EF(RBE)_n = 55$

$m = 300$ grams

$T_{eff} = 46$ days

$F_u = 0.1$

GI TRACT DOSE EQUIVALENT CALCULATION

CLASS PROBLEM

Air sampling on 4 consecutive days indicated tungsten-187 concentrations of 5000 pCi/cm^3, 3500 pCi/cm^3, 2000 pCi/m^3 and 1500 pCi/cm^3 respectively. If a person was in this environment for all four days what would be his total infinite D.E. to the lower large intestine? What would be the D.E. to the stomach on day one only? (^{187}W is generally in an unsoluble form and the LLI is the critical organ). Assume no ingestion of Tungsten-187.

$\cong$ E(RBE) for LLI = 0.36

f_1 = 0.1

$T_{\frac{1}{2}}$ = 1.0d

$\cong$ E(RBE) for S = 0.44

Class Problems: CORRELATION OF EXPOSURE AND DOSE

1. A thimble chamber is inserted in a phantom at a depth equal to the equillibrium thickness of tissue for Cs-137 gamma rays (.662 MeV). An exposure of 50 R is measured.

   a. What are the absorbed doses for tissue and bone?

   b. If the chamber measured exposure from the same source at the same distance from the source, but in air rather than tissue, would the indicated exposure be higher or lower than 50 R? Why?

2. A source of 6 MeV x-rays produces an exposure of 25 "R". What is the absorbed dose in water?, and, who cares?

Quantities and Units of Radiation

I. INTRODUCTION

The structure and meaning of currently accepted definitions used in quantitative determination of radiation fields must be understood. Without a physically consistent, realistic, and measurable description of the radiation field, the clinician, radiologist, or technologist could not utilize radiation with reproducibility or safety, nor could the effects of radiation on living organisms be ascertained. The concepts discussed in this outline represent only part of a set of radiation quantities and units established by the International Commission on Radiation Units and Measurements (ICRU) in its Report Number 11, Radiation Quantities and Units, published in 1968.

II. QUANTITIES AND UNITS

The ICRU has standards which clearly delineate radiation quantities and radiation units.

A "quantity" may be thought of as a description of a physical concept or principle. The magnitude or measure of a quantity is a "unit." Fundamentally, therefore, the quantity is the more important. The unit places limits upon, but will not serve to define, the quantity. For example, the concept of length is a quantity; the meter is a unit of length.

An internationally accepted system of writing and abbreviating units has been established. To avoid confusion with the name of the man for whom a unit may be named, the name is capitalized when referring to the man (Roentgen) but when referring to the unit, the name will be written in lower case (roentgen).

The abbreviation for the unit is, however, capitalized (R). In cases where the abbreviation conflicts with another accepted symbol, a combination of letters, usually the first and last, is used. An illustration is seen in the case of the unit curie. The abbreviation used is Ci, as other possible symbols conflict with the symbol for coulomb and with common chemical symbols.

A. Radiation Quantities

Radiation may be divided into two classes: ionizing and non-ionizing. X rays, for example, are classified as ionizing radiations by virtue of their energy. Ionizing radiations, however, include many types of radiations in addition to x rays. The ICRU has considered ionizing radiations in two categories:

1. Directly ionizing particles or charged particles (electrons, protons, alpha particles, etc.), which have sufficient kinetic energy to cause ionization by collision; and
2. Indirectly ionizing particles or uncharged particles (neutrons, gamma rays, x rays, etc.), which can interact and liberate directly ionizing particles.

Quantities describing the effects of the interaction of directly and indirectly ionizing radiations with matter have been developed to cover many aspects of the interaction processes. For practical radiation protection measurements and control, only four quantities are generally utilized. These will be discussed in greater detail in the following material.

B. Exposure

Historically, the most important term associated with radiation exposure has been the roentgen. So, after a series of redefinitions, the roentgen has been chosen as the unit for the quantity exposure. The current definition of exposure is:

> The exposure (X) is the quotient of ΔQ by Δm, where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons (negatrons and positrons), liberated by photons in a volume element of air whose mass is Δm, are completely stopped in air.
>
> $$X = \frac{\Delta Q}{\Delta m}.$$

Several important restrictions applying to the quantity are immediately apparent from the wording of the definition:

1. The medium in which exposure is defined is air; no other medium is acceptable.
2. The radiations for which exposure is defined are photons (x ray and gamma).
3. The effect being measured is ionization of the air.
4. All electrons liberated in the ionizing processes must be stopped in air.

The last restriction serves to impose upper limits on the maximum quantum energy which may be directly measured in terms of exposure, because the range of the electrons liberated increases as a function of the energy. A chamber (see a discussion of the free air chamber) which measures exposure directly must have dimensions such that the distances from the electrodes to the sites of interaction are greater than the maximum range of the secondary electrons. For example, a chamber intended to measure exposure resulting from a beam of 2 MeV photons would require overall dimensions greater than 15 meters, because the maximum range in air of 2 MeV electrons which may be liberated is on the order of 7.5 meters.

The meaning of the symbol Δ (read delta) is best illustrated by considering the fact that the interaction of radiation is not continuous. Interaction locations are discrete sites which can only be described statistically. If the measuring volume is too small, a single measurement of the effect may include no interaction or, through chance, several interactions may have occurred within the volume. Therefore, an average value must be determined. This effect of random variations obtained by a series of measurements is shown in the left region of the curve in Figure 1. As the volume is increased, the effect of the larger volume is to average the effects measured in a series of smaller volumes. The result approaches closely the true average, as indicated in the center portion of the curve. A continued increase in the volume would now include regions outside the radiation field, and the measured values would decrease, as shown on the right. In short, the measurement of radiation fields involves statistical averaging procedures; the symbol Δ will precede the symbols for quantities that may be involved in such averaging procedures.

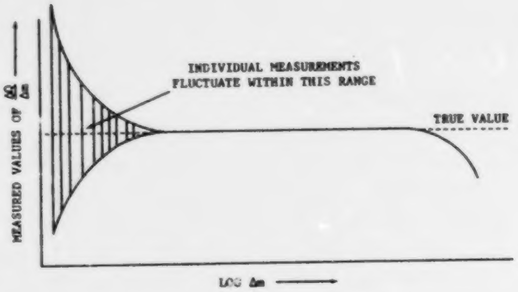

Figure 1.--Detector Response vs. Volume

C. Absorbed Dose

Exposure, as noted earlier, is limited to measurement of the ionization in air produced by x or γ radiations. This quantity is, of course, extremely limited: Many types of radiation exist, and the material of interest in which interaction occurs in most cases is not air. Additionally, ionization produced by the radiation may not be the effect which is most usefully evaluated. "Absorbed dose" is a quantity much more general in its structuring. It is defined as follows:

> The absorbed dose (D) is the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted

by ionizing radiation to the matter in a volume element, and Δm is the mass of the matter in that volume element.

$$D = \frac{\Delta E_D}{\Delta m}.$$

The following points are to be seen in the definition:

1. Any type of ionizing radiation (directly or indirectly ionizing) is included.
2. Any material may be used in making the measurement.
3. The effect observed is the energy imparted by the radiation to the matter in the volume element.

Most often a direct measurement of absorbed dose will be carried out by calorimetry, since temperature changes--which directly reflect the energy input to the mass (if one excludes possible changes from associated chemical energies)--are relatively easy to measure. Again, it must be pointed out that selection of the size of the mass is important as statistical averaging procedures apply.

The energy imparted to the matter in the volume element is not necessarily equal to the amount of energy removed from the beam. Secondary electrons, for example, may carry some energy to matter in adjacent volumes. The energy lost is related to another quantity, "kerma" (kinetic energy released in material).

Because absorbed dose is a general quantity applying to any radiation in any material, it could certainly be applied to x radiation in air. Thus a relation between absorbed dose and exposure may be established in air or in other media.

D. Dose Equivalent

Research has shown that the effect of ionizing radiations on biological systems is not related exclusively to absorbed dose. The effects observed depend on many factors and include:

1. Type of radiation
2. Energy of the radiation
3. Distribution and/or fractionation of the radiation
4. Biological endpoint chosen
5. Time at which the endpoint is evaluated
6. Species and strain of the organism utilized.

Many other factors, such as the administration of certain drugs, also influence the response to radiation. In an effort to provide a comparable numerical basis for the effects of various types of radiation for protection purposes, a quantity termed the "dose equivalent" (DE) has been defined as:

> The product of the absorbed dose (D), quality factor (QF), and other necessary modifying factors:

$$DE = D\ (QF)\ (\ .\ .\ .\ ).$$

Depending upon the effect chosen for evaluation, the result obtained when the effects of two types of radiation are compared (frequently termed in radiobiological research the "relative biological effectiveness" or RBE) may vary widely. A representative value for the RBEs is selected by a committee to be used for radiation protection purposes. This value is termed the "quality factor" (QF).

Typical quality factors, given here, are taken from Rees, D. J., Health Physics: Principles of Radiation Protection (London: Butterworth, 1967):

Quality Factor	Type of Radiation
1.0	X rays; γ rays; electrons; and β rays with E_{max} greater than 0.03 MeV
1.7	β rays with E_{max} not greater than 0.03 MeV
10.*	Neutrons and protons up to 10 MeV
10.	Naturally occurring α particles
20.	Heavy recoil nuclei

---

*30. in the case of irradiation of the eyes.

E. Activity

A quantity is necessary to describe the rate at which a radionuclide undergoes nuclear transformations. Historically, radium was used as a standard, but ICRU recommendations have established a quantity which is independent of any particular substance and depends only on measurable quantities, i.e., the number of transformations occurring and the time during which these emissions took place. The quantity involved is "activity" and is defined as follows:

> The activity (A) of a quantity of a radioactive nuclide is the quotient of ΔN by Δt where ΔN is the number of nuclear transformations which occur in this quantity in time Δt.
>
> $$A = \frac{\Delta N}{\Delta t}.$$

Activity applies only to the number of nuclear transformations taking place per unit time and is not directly related to the exposure rate, absorbed dose rate, or dose equivalent rate due to the radionuclide.

F. Units

Each of the quantities discussed has a measure or "unit" assigned to it. Exposure is expressed in terms of the equation

$$X = \frac{\Delta Q}{\Delta m}$$

where Q represents electrical charge (produced by ionization) per unit mass of air. Hence, any units of charge over mass would conform with the definition. The ICRU has, however, established a special unit, the use of which is restricted to measurement of exposure only. The unit of charge used is the "coulomb," and the unit mass is the "kilogram." Specifically,

$$1 \text{ roentgen} = 2.58 \times 10^{-4} \text{ coulombs/kilogram*}$$

Absorbed dose, defined in terms of energy deposited in a mass, would demand units of energy (joules, for example) per unit mass (kilograms). Again, a special unit has been defined which is used in referring to absorbed dose:

$$\begin{aligned} 1 \text{ rad} &= {}^{1}/_{100} \text{ joule/kilogram} \\ &= 100 \text{ ergs/gram.} \end{aligned}$$

The unit of dose equivalent is the "rem," which is obtained by multiplying the dose in rads by the appropriate quality factor and other modifying factors. The ICRU notes in its report that this statement ". . . does not cover a number of theoretical aspects (in particular the physical dimensions of some of the quantities) . . . " but that " . . . it fulfills the immediate requirement for an unequivocal specification of a scale that may be used for numerical expression in radiation protection." In short, since dimensionality is ignored, rems = rads × QF. Since the QF for x and gamma radiation is 1, the number of rems is identical to the absorbed dose in rads for these radiations.

The special unit for activity is the "curie." The commission has recommended that steps be taken to redefine the curie as

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ s}^{-1} \text{ (exactly).}$$

The earlier definition of the curie was based on the activity of the radon gas in equilibrium with one gram of radium. Recent measurements have shown that the activity associated with this standard is $3.61 \times 10^{10} \text{ s}^{-1}$ and hence the unit has been redefined as a number independent of any given radioactive nuclide.

III. PRACTICAL CONSIDERATIONS

In the application of instrumentation to the assessment of the radiation fields, care must be taken to select instruments which will truly indicate or measure the radiation quantity of interest. Exposure can only be measured directly by an air-filled device which measures ionization in air. In practice, most exposure measuring instruments are related to a free-air chamber, and do not actually measure exposure directly. Most of the ionization produced and measured originates in the chamber wall--which is hopefully an "air equivalent" material.

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*The magnitude of this unit does not differ from the magnitude of the previous definition.

IV. SUMMARY

Certain of the salient features of radiation quantities and units are presented in the following table:

Associated Features	Quantities		
	Exposure	Absorbed Dose	Dose Equivalent
Radiation types	x- or gamma ray	all ionizing	all ionizing
Media in which effects are measured	air	any	biological system
Effects observed	ionization	energy deposited	biological effect
Units	roentgen	rad	rem

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THE PROBLEM OF RADIATION SURVEILLANCE

J. W. Mullins*

I INTRODUCTION

Environmental radiation surveillance may be conducted for a number of reasons. It may be conducted to provide information for assessing the exposure dose to a population, for testing the adequateness of source control measures, for following tracers in research studies, for observing gross trends in air or water, for measuring radionuclide concentrations in specific media, or for other reasons. The general procedure for radiation surveillance is not unlike that for other environmentally oriented sampling programs. In fact, radioactivity is sometimes treated as only another contaminant in assessing total air or water quality (National Air Sampling Network of PHS and National Water Quality Network of FWPCA). In environmental radiation surveillance it is necessary to consider the sources of radioactivity, environmental movement, the objectives of sampling programs, the analytical methods necessary to produce valid data, the interpretation of the resulting data in light of established guides, and the necessary public health or protective actions.

II ENVIRONMENTAL RADIATION SURVEILLANCE

To constitute an important biological hazard a radioactive material must be:(1)

1 Available in sufficient quantity.

2 Efficiently transferred through the aquatic and terrestrial food chain to the human diet.

3 Highly assimilated by one or more specific body tissues. (In evaluating such criteria, it should not be neglected, however, that some radionuclides may yield significant doses just in passing through the body even though not assimilated.)

4 Biologically retained within the body for a long time.

5 Have a reasonably long physical half-life.

Based upon these criteria, some of the most important radionuclides with regards to man's total intake are strontium 89, strontium 90, cesium 137, iodine 131, radium 226, and carbon 14. Iodine 131 can be a significant problem in fresh fallout from nuclear weapons tests, in reactor releases,(3) and near chemical processing plants. Strontium 89, strontium 90, and cesium 137 are present in fresh fallout from nuclear weapons testing and reactor operation. Radium 226, a naturally occurring radionuclide, has been observed in streams near uranium mills, and in ground waters in various geographic locations. Carbon 14 is both man-made and naturally occurring. Other nuclides may assume significance under special circumstances. For instance, one of the most significant contaminants in the Columbia River is phosphorus 32.(2) This results from neutron activation of minerals in cooling water discharged from the reactors at Hanford. Many other radionuclides have been identified in environmental samples, e.g., tritium (H-3), barium-lanthanum 140, zirconium-niobium 95, ruthenium 103, ruthenium-rhodium 106, cerium 141, cerium-praesodymium 144, zinc 65, manganese 54, etc.

A The sources of radioactive contaminants in the environment include: natural radioactivity, uranium ore mining and milling, reactor operations (including chemical processing of spent fuels), radioisotope users, and weapons tests.

1 Natural background(4)

The magnitude of background radiation is of significance for comparison with the radiation exposure burden being

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superimposed by man. Cosmic radiation may produce significant external exposure depending on altitude and latitude. Cosmic radiation also produces induced radionuclides through interactions with atmospheric nitrogen, the result being carbon 14 and tritium.

Terrestrial background radiation results from the presence of the uranium, thorium, and actinium decay series plus about twelve singly occurring radionuclides. Significant examples are radium plus its daughters and potassium 40. These radionuclides, originally present in the earth's crust, are gradually leached into waters, evolved into the atmosphere, or taken into foodstuffs.

2 Uranium ore mining and milling

The uranium industry is potentially an environmental as well as an occupational hazard. The main problem associated with the uranium industry is occupational, associated with breathing contaminated dust and/or radon. However, discharge of waste can result in an environmental problem. On the Animas River for example the activity concentration of radium rose above the radiation concentration guide, before suitable action was taken.(5)

3 Reactor operations

There are many types of reactors and their effect on the environment varies with type.(6)

In operation, the coolant may be a source of contamination. At Brookhaven, air is drawn through the core to cool the reactor and then discharged through the stack. This air contains A^{41} from neutron activation of A^{40} and possibly active dust particles. At Hanford the reactors are water-cooled and the effluent water is discharged into the Columbia River. This water contains neutron activation products, corrosion products from fuel element cladding and reactor parts and fission products leaking from the fuel elements. Recirculating water-cooled reactors may produce the same types of impurities although these are generally contained. Nuclear powered ships normally use water as primary coolant. The water is usually treated with ion exchange resin and disposal of some solids and liquids may be done at sea.

Chemical reprocessing of fuel presents the greatest potential for environmental contamination. This process separates the uranium, plutonium and fission products which the fuel elements contain. The initial separation yields hundreds of millions of curies of fission products which are then stored indefinitely. The uranium and plutonium is not yet pure however and still contains thousands of curies of fission products. The complete purification produces voluminous quantities of aqueous waste which may be discharged to the environment. Also, gaseous wastes are produced in the separations process, mainly krypton 85 (half-life 9.4 years), xenon 133 (5.3 days) and iodine 131 (8 days). The most critical nuclide is usually iodine 131. Solid wastes, such as sludge from chemical processes, cladding from fuel elements, etc., may be buried.

4 Isotope users

The greatest percent of radionuclides produced for industrial, hospital, or research are prepared in some sort of solid or encapsulated form, and as such are of primary concern with regard to their potential as external exposure hazards.

Liquid wastes may be a problem from users of large quantities of specific radionuclides, but each establishment will normally have its own disposal systems. Users of small quantities of nuclides, say microcurie amounts, will normally discharge directly to a sewer.

5 Weapons tests

In 1951, 12 nuclear devices were detonated at the Nevada Proving Ground.(7)

The United States total of announced detonations from 1961 to 1964 is about 180.(8) More important than the number of devices is their energy yield which is an indication of the quantity of fission products produced. Information released at the 1963 Congressional Hearing on Fallout, Radiation Standards, and Countermeasures showed that 193 megaton fission yield equivalent had been released to that data (See Table 1).(9)

As a result of detonations of nuclear weapons, large quantities of radioactive materials have been introduced into the atmosphere. Small amounts of these materials have been and are being deposited throughout the world. Such deposition is known as nuclear weapon fallout.

B Movement

Radioactive materials may be transported from one location to another by means of movement of air masses. Possibly eighty to ninety percent of all fallout materials reaching the earth is brought down in precipitation. The waters in streams, however, contain only about one percent of the activity present in the precipitation. The major contributors to the aquatic environment, therefore, are from precipitation directly deposited on streams or lakes, and liquid wastes from reactor operations, chemical processing, and radionuclide users.

Radionuclides in water may gain access to the diet through aquatic plants and animals either by surface contamination or by biological uptake. The latter is influenced by the concentration of radionuclides, the stable mineral content of the aquatic environment, and the position of a particular plant or animal in the aquatic food chain.(2, 10, 11) Vegetative organisms, such as phytoplankton and filamentous algae, which absorb nutrients directly from the water, accumulate the greatest concentration of radioactive material. Next are the zooplankton and

TABLE 1. APPROXIMATE FISSION AND TOTAL YIELDS OF NUCLEAR WEAPONS TESTS CONDUCTED IN THE ATMOSPHERE BY ALL NATIONS

(Yield in Megatons)

Inclusive years	Fission yield		Total yield	
	Air	Surface	Air	Surface
1945 to 1951. . . .	0.19	0.52	0.19	0.57
1952 to 1954. . . .	1	37	1	59
1955 to 1956. . . .	5.6	7.5	11	17
1957 to 1958. . . .	31	9	57	28
Subtotal	37.8	54	69.2	104.6
1959 to 1960. . . .	(1)	(1)	(1)	(1)
1961	25(2)		120	
Subtotal	63	54	189	105
1962	76(2)		217	
Total	139	54	406	105

(1) Test moratorium.

(2) The small yield tests conducted in Nevada do not contribute significantly to the worldwide distribution of strontium-90 to which this summary is related.

bottom animals which feed on the plant mineral, and then the juvenile and small fish which feed principally on these animals. At the end of the chain are the game and food fish which in turn feed on the juveniles.

Reconcentration of radioactive materials has been well demonstrated in studies of aquatic food chains in the Columbia River. A general decrease in the concentration of beta emitting radioactive materials was observed in passing from vegetative organisms through bottom animals and utility fish to game fish. Despite this decrease, however, fish may contain gross beta activity in concentrations 10 to 200 times that in the water. It is actually possible, under such circumstances, to have a situation where water may meet drinking criteria and yet fish grown therein be unsuitable for human consumption.

The transmission pathways of radioactive material through the terrestrial food chain to man are shown in Figure 1.(12, 13) The radioactive material is scavenged from the atmosphere by meteorological processes, particularly rain. The most serious contamination problems arise from direct deposition of the radionuclides on animal feed crops or on food crops directly consumed by man. Following the initial deposition on vegetation the radioactive materials tend to be removed by various processes, such as being washed off by rain or being blown off by the wind. The extent to which such removal occurs depends on a number of considerations, including particle size, chemical properties of the material deposited, and environmental or biological factors.

For any particular radionuclide, it is necessary to know the critical pathway, i.e., the route by which it reaches man, before it is possible to sample for it and estimate its effect on man.

C Sampling Programs or Surveys

Many factors need to be considered before a sampling program is put into effect. The kind of program required will vary with the specific objectives, ranging from routine surveillance for evaluating general radiation levels to special programs for specific radionuclides important in assessing radiation exposure of populations.

Many of the problems involved in surveillance are related to the size and variability of the natural environment.

Depending upon the objectives of the particular sampling program it may be necessary to attempt to measure the concentration of radionuclides in the air breathed by persons in a city or county or State. It may be necessary to evaluate the activity concentration of radionuclides in milk in a milkshed containing thousands of cows and serving many thousands of people. It may be necessary to evaluate the activity concentration in a large rapidly flowing river or a lake or an estuary, or it may be necessary to evaluate the radionuclide intake of a population and hence the resulting dose by analyzing air, water or food samples.

In establishing the objectives of a sampling program it is necessary to keep in mind such problems as variety in terrain, meteorology, agricultural practices, diet, and economic situations from one area to another in a state or country.

Unless the survey is planned and executed properly, the result may be a meaningless accumulation of data (or of too much or too little data), rather than an orderly, logical program which produces useful data.

Common sense criteria may help in deciding what to sample. If one is interested in measuring intake, then one samples drinking water rather than raw surface water. If there is a high possibility for the release of a specific nuclide, when it is desirable to sample a media which will concentrate this nuclide. It may be that one nuclide is the most critical due to local dietary habits and levels of discharge. If this is the case, it may be necessary to sample only a limited number of media.

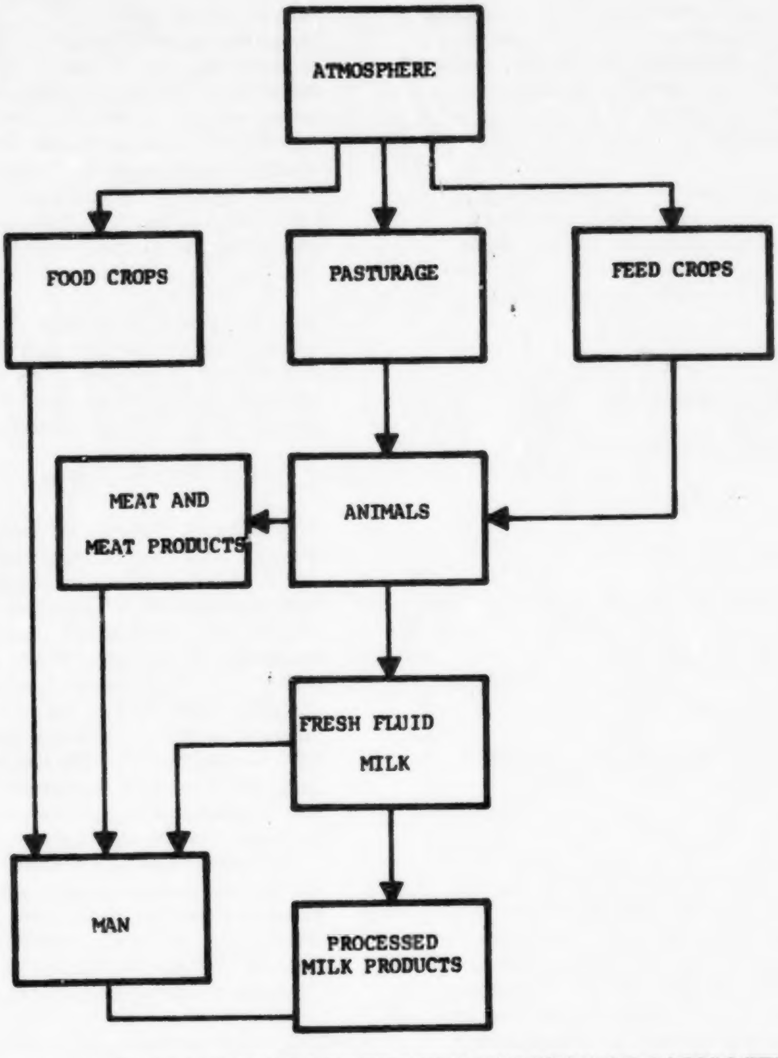

ATMOSPHERE
FOOD CROPS
PASTURAGE
FEED CROPS
MEAT AND MEAT PRODUCTS
ANIMALS
FRESH FLUID MILK
MAN
PROCESSED MILK PRODUCTS

Figure 1. IMPORTANT STEPS IN THE TRANSMISSION OF RADIOACTIVE MATERIAL THROUGH THE FOOD CHAIN TO MAN

Depending on the objectives, it may be necessary to design a survey to represent the environment. Representative sampling may be performed using judgment or random design. The data resulting from a random survey are limited only by the statistics of the particular situation, that is they stand or fall on their own merit. In judgment sampling, the judgment decisions may tend to bias the results.

Some of the considerations involved in putting a program into effect are listed below.(14) It should be noted that these factors all require considerable attention and are to a large part, interrelated.

1 Extent of the program
  a Number of samples
  b Frequency of sampling
  c Type of samples
2 Sampling procedures
  a Location of sample stations
  b Grab or continuous
3 Analysis techniques
4 Staff, equipment, and administrative requirements.

D Analysis

In the operational phase of environmental radiation surveillance the laboratory may be thought of as a "black box" in which environmental samples are placed to be analyzed. The "black box" will prepare the sample, perform chemical separation where necessary, mount the samples for counting, count the samples under quality controlled conditions, calculate the results, and hand out a number (statistically valid from laboratory and counting room quality control) which is an activity concentration, i.e., picocuries per unit volume or weight.

E Data Interpretation

The data resulting from the analysis of environmental samples can be subjected to statistical analysis. If the objective of a program is to detect an actual change in the activity concentration in the environment from one location to another, it may be becessary to resort to statistical techniques such as comparisontests and analysis of variance. Insignificant differences between locations may result from the expected statistical variation in sampling and measurement or from fluctuations in the natural environment.

It is important to be able to differentiate between this random variation and true differences in levels. The comparison tests of the type described are the only way of doing this objectively.

F Public Health Significance

The activity concentrations of environmental samples are important in relation to the ultimate effect on man. The original work on radiation protection standards was done by the International Commission on Radiation Protection (ICRP) and the U.S. National Committee on Radiation Protection (NCRP). The NCRP has published its recommendations in several handbooks, e.g., NBS Handbook #69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure."(19) The Federal Radiation Council (FRC) has applied these concepts to environmental exposure and has developed guidelines for total exposure (Radiation Protection Guides)(15) and for intake of certain nuclides (Radiation Concentration Guides).(16)

The Federal Radiation Council has issued normal peacetime guides for intake (picocuries per day) of the following nuclides: strontium 89, strontium 90, iodine 131, and radium 226.(16) In addition, the council has warned that the amount of additional carbon 14 produced as a result of increased weapons testing will increase the total mutation rate in humans more than all the other fission isotopes combined.(17) The Public Health Service has designed drinking water standards for strontium 90, radium 226, and gross beta activity.(18)

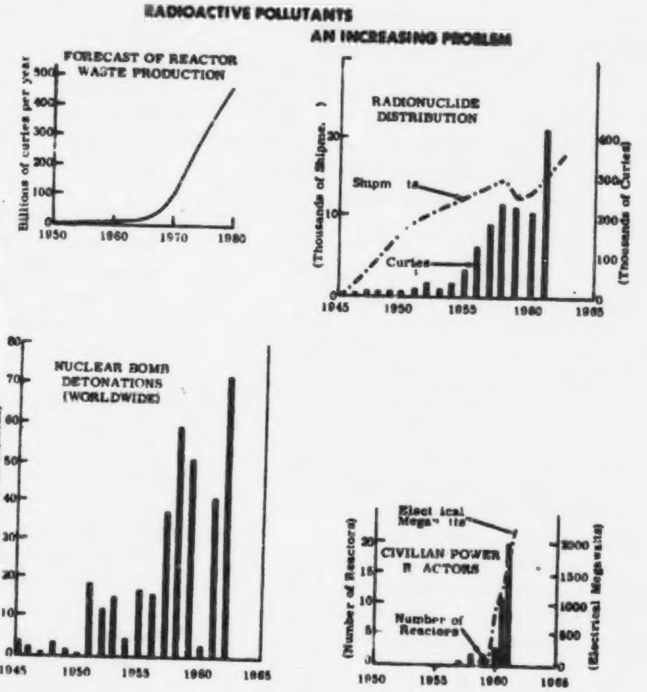
G Public Health Action

In the event that the radioactivity concentration guides are exceeded, it may become necessary to resort to protective actions to limit the intake of radionuclides into the body. Situations calling for public health or protective actions might be 1) an industrial accident involving a nuclear reactor or a nuclear fuel processing plant or 2) a release of radioactive materials from the detonation of nuclear weapons or other devices. Protective Action Guides, or levels at which public health action may become necessary have been developed for iodine 131, strontium 89, strontium 90, and cesium 137.(12, 13)

III SUMMARY

The increasing magnitude of radiation producing sources is typified in Figure 2. Simultaneous with this increase, the recommended maximum permissible levels for radiation exposure (Radiation Protection Guides) have been decreased many fold. The magnitude and sequence of this decrease is shown in Figure 3.

In order to assure the maintenance of this delicate balance, it is necessary to design sampling programs very cautiously. Public health and other health related personnel must periodically evaluate each sampling program to insure that its objectives are being satisfied and that the sampling program is more than a mechanism for collecting questionable or useless data.



RADIOACTIVE POLLUTANTS
AN INCREASING PROBLEM

Figure 2

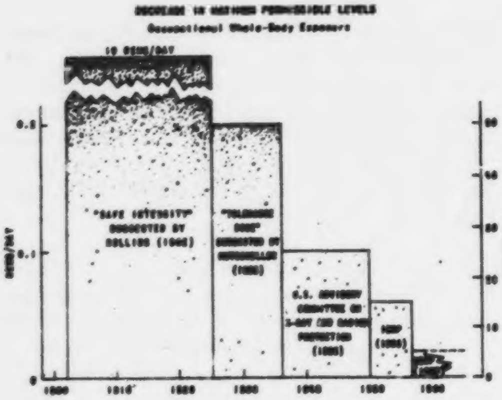


Figure 3

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Maximum Permissible Dietary Contamination after the Accidental Release of Radioactive Material from a Nuclear Reactor

Report to the Medical Research Council by its
Committee on Protection Against Ionizing Radiations*

After the accident to No. 1 pile at Windscale on October 10, 1957, the Atomic Energy Authority asked the Medical Research Council for advice on the maximum intake of certain radioactive isotopes that should be regarded as permissible, under emergency conditions, for members of the general population living in, or deriving food from, an area contaminated owing to an accident to a reactor.

The Council's Committee on Protection against Ionizing Radiations, together with its Subcommittees on Internal and External Radiations, has considered this problem, and concludes that the intake of radioactive materials by ingestion of contaminated food would generally be the limiting source of hazard after any such accident. Intake by inhalation, or radiation from the exterior, would become of importance only in rather special circumstances.

In the following report, therefore, the Committee proposes maximum permissible levels of dietary contamination for the relevant isotopes in the emergency conditions envisaged. In proposing these levels, the Protection Committee has used the fullest information available on the radiation doses that would be delivered to different body tissues and at different ages by the isotopes concerned, and on the ways in which these materials would enter the body. The Committee wishes to stress, however, that knowledge of the metabolism of radioisotopes is continually increasing and that the subject of permissible doses is constantly under review. In several instances where information has been inadequate, we have used the more cautious, rather than the more likely, assumption; and it is probable that some of our recommended levels are lower than may be regarded as permissible when more information becomes available - for example, on the duration of dietary contamination to be expected following a reactor accident.

The main problem relates to the intake in food of a small group of radioactive isotopes which are produced in high yield by fission of reactor fuel, and which in addition becomes highly concentrated in certain organs of the body. The Committee's recommendations are expressed in terms of the maximum permissible daily intake of each of these isotopes at various ages, having regard to the metabolism of each element and the period during which the contamination of the food supply is likely to continue.

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In view of the specialized problems involved in the assessment of hazards from internal irradiation, estimates are given of the absorbed dose or doserate of radiation likely to result in the organs concerned from the proposed levels of intake. It is hoped that these calculations will make it easier to review the significance of the present proposals, and to compare them with the recommendations of the International Commission on Radiological Protection (I.C.R.P.).

It must, however, be appreciated that the recommendations of I.C.R.P., which have been taken into full consideration in the present proposals, do not refer to the problem of an emergency exposure of members of the general population. I.C.R.P. has made recommendations on the maximum permissible intake of numerous radioisotopes for those persons occupationally exposed to radiation. The Commission added that "in the case of the prolonged exposure of a large population the maximum permissible levels should be reduced by a factor of ten below those accepted for occupational exposure".

This recommendation was clarified in 1956, when it was stated that it did not refer to the entire population but to "persons who might be exposed unknowingly in the neighborhood of a plant or source of radiation". It was further stated that "under the conditions at present envisaged, the regions in which the 10% level might be reached would contain a very small fraction of the population and, therefore the average organ doses per individual of the whole population would be very much lower than 10% of the maximum permissible organ doses for occupational exposure". It is clear that the permissible levels should be lower for persons exposed continuously in the neighborhood of a plant or source of radiation than for those who are exposed occupationally, since the former group may include children and might apply to lifelong exposure rather than during the period of working life. It is likely, moreover, that those occupationally exposed would be under detailed health surveillance and that the amounts of radiation received by each individual would be known. However, the I.C.R.P. recommendations are estimated on the basis of prolonged exposure, and the levels permissible for transient intake may be higher than those recommended by the Commission for continuous intake.

The main effects requiring assessment are the irradiation of the thyroid gland by radioiodine, of the bone and bone marrow by radiostrontium, and of the whole body by radiocesium. The position is simplified since (a) iodine-131 will be the major contributor to thyroid irradiation, other forms of radioiodine being negligible in comparison, and (b) strontium-90 will be of greater importance than strontium-89 in the irradiation of bone. The concentration of either iodine-131 or strontium-90 will therefore, in general, determine the suitability of food for consumption. Since fresh milk will be the main source of these isotopes and of radiocesium, the concentrations in milk will normally provide a valid basis for control measures.

Since radioiodine is concentrated mainly in the thyroid and radiostrontium mainly in bone, these two materials do not to any serious extent cause irradiation of the same tissues. The recommended maximum intakes of them would not, therefore, be altered in the event of mixed contamination, except that when the intake included both strontium-89 and strontium-90 the levels permissible for each of these isotopes should be reduced proportionately, since both cause irradiation of bone. Radiocesium, however, causes irradiation of the whole body, and consequently the presence of appreciable cesium-137 contamination would involve a reduction in the permissible intakes of radioiodine and radiostrontium.

Recommendations

The following recommendations are of the maximum permissible daily intakes, attributable to an accident and in the period following it, of the four isotopes which might be of the greatest importance in determining the suitability of food for consumption - namely, iodine-131, strontium-90, strontium-89, and cesium-137. The values take into account the likely sequence of rise and fall of food contamination, and are expressed as those permissible at the time of maximum contamination soon after the accident. It is estimated, as described below, that these levels of intake, if continued during the likely course of the contamination, would deliver certain doses of radiation to the tissues most heavily irradiated. These total doses are about equal to the annual doses regarded as the maximum permissible ones for these tissues by the I.C.R.P. for those occupationally exposed to radiation. Thus the maximum intakes of iodine-131, proposed for various ages correspond to a total thyroid irradiation of 25 rad, as compared with a maximum annual value of 30 rad during occupational exposure; the intakes for strontium-89 and strontium-90 correspond to a total of 15 rad and an annual rate of 1.5 rad per year respectively, at sites of highest concentration in bone, as compared with an occupational rate of 15 rad per year in bone; and the cesium-137 intake gives a total dose of 10 rad to the whole body, which is less than the maximum annual occupational value of 12 rad for whole-body external irradiation, although greater than the average value of 5 rad appropriate to a prolonged continuing exposure.

The recommendations are intended to apply to accidental contamination causing significant exposure of numbers of people small compared with one-fiftieth of the whole population of the United Kingdom, and the Committee has taken into consideration that it is possible but unlikely that the same persons might be significantly exposed to a second accidental release of radioactive material. The following account is intended to summarize and illustrate, rather than to give in detail, the information reviewed by the Committee and the recommended precautions in the event of accident.

Radioiodine - The recommended maximum permissible initial daily intakes for iodine-131 are 60 mμc per day up to age 6 months, rising to 110 mμc per day at age 3 years, 300 mμc per day at age 10 years, and 1,300 mμc per day at ages over 20. These values assume that the amount of iodine-131 in the food and in the thyroid decrease, at a rate no faster than that due to radioactive decay. Irrespective of the rate of decrease, the maximum permissible total intakes of iodine-131 attributable to the accident would be 650 mμc, 1,200 mμc, 3,400 mμc, and 15,000 mμc for the ages given above.

Radiostrontium - For the strontium isotopes the recommended maximum permissible daily intakes are 2 mμc per day for strontium-90 and 200 mμc per day for strontium-89, at any age. When the intake includes both isotopes the levels of each should be reduced accordingly.

Radiocesium - In the case of cesium-137 the recommended maximum permissible daily intakes are 60 mμc per day at birth, rising to 150 mμc per day at age 6 months and 1,150 mμc per day at ages over 20. These values assume that the amounts of cesium-137 in the food and in the body decrease at rates such that the effective half periods are 10 weeks and 20 weeks respectively. The corresponding maximum permissible total intakes are 6 μc, 15 μc, and 115 μc.

Comments on the Recommendations

IODINE-131

The Committee has considered that the maximum intake of radioactive iodine should be such that the mean radiation dose to the thyroid gland would not exceed 25 rad. The recommended intakes will depend upon the thyroid size and iodine uptake from food at different ages. The mass of the gland was taken to be 1.8 g. from birth to 6 months, 3.4 g. at age 3 years, 9.2 g. at age 10 years, and 25 g. in the adult, the uptake falling from 50% in childhood to 30% in adult life.

For the calculation of emergency levels of the daily intake of iodine-131, fresh milk is regarded as the most important source of the isotope. If pastures are contaminated with iodine-131 and no loss of the isotope occurs from the herbage except by radioactive decay, the iodine-131 content of milk from the cows grazed on these pastures will reach a maximum value about three days after the contamination and, after the first week, fall with the half period of iodine-131. For children fed on liquid milk only, the maximum thyroid irradiation would be likely to occur at an age of about 6 months, since the thyroid size increases very little from birth until this age, whereas the milk intake may increase with body weight until this age. The maximum permissible intake of 60 mμc per day corresponds to a peak iodine-131 concentration in milk of 0.065 μc per liter, assuming a milk intake of 0.9 liter per day at the age of 6 months. This maximum intake would correspond to a total ingestion of 0.65 μc, which, with 50% uptake into the 1.8 g. gland and prolonged retention, would give a total mean dose of 25 rad to the gland. The values proposed at different ages correspond to the same total mean dose.

It may be noted that the limit of 0.065 μc per liter could be raised considerably provided that young children were fed on dried milk, or liquid milk, from uncontaminated sources. An initial concentration of 0.3 μc per liter would permit normal intakes for children over the age of 3 years (assuming a milk intake of 0.3 liter per day at this age).

Radioactive Strontium

The bone-seeking radioactive isotopes will have a very non-uniform distribution in the skeleton unless the intake is over a long period of time. A basic problem in estimating maximum permissible levels for emergency exposure is whether the calculations should be based on mean radiation dose in the skeleton or local dose at sites of maximum concentration. In the absence of a definite answer to this question, the calculations have been made on the assumption that a certain radiation dose or dose-rate is not to be exceeded at any site of isotope concentration in the bone. If future work shows that mean skeletal dose, and not this local dose, is the significant criterion it will be possible to increase the values of dietary intake that have been proposed.

A second difficulty arises in that one of the strontium isotopes, strontium-90, has a long half-life (28 years) while the other, strontium-89 has a much shorter half-life (53 days). It would not be reasonable to adopt the same criterion for both isotopes. It was considered, therefore, that for the long-lived strontium-90 the maximum permissible value for emergency exposure should be calculated on a basis of the maximum yearly dose-rate at a site of concentration, while for the short-lived strontium-89 the criterion should be the maximum total radiation dose delivered at any such site. The Committee recommended that in the case of strontium-90 the maximum permissible local dose-rate in mineral bone should be 1.5 rad per year and in the case of strontium-89 the maximum permissible local dose should be 15 rad. Both maximum and mean doses to the bone marrow will be substantially less than those to mineral bone.

Level for Strontium-90 - New bone deposited during the growing period in children will be formed from circulating calcium, which will be derived largely from the current dietary intake contaminated with radiostrontium, but partly also from less contaminated calcium released from older bone during remolding processes. Moreover, it has been shown that, after the ingestion of a diet containing both strontium and calcium, the ratio of strontium to calcium deposited in bone is about one-quarter of that in the diet. This change in the ratio results from differences in the absorption and excretion of the two elements.

If the diet contains 2 mμc of strontium-90 associated with a normal calcium intake of 1 g. daily, the strontium-90 concentration at sites of new bone formation will therefore not exceed one-quarter of this dietary ratio, or 0.6 mμc per g. of calcium. The dose rate in bone at this concentration is rather less than 1.5 rad per year.

Level of Strontium-89 - The level of dietary contamination of strontium-89 which will give a total dose not exceeding a given value at any local deposit can be calculated by integrating the dose rate over time, using 53 days as the half-life. The value for the concentration of strontium-89 in bone which will give a total dose not exceeding 15 rad at the site of the deposit is 50 mμc of strontium-89 per gram of calcium, corresponding to a daily dietary intake of 200 mμc.

Duration of Intake - The shorter the duration of intake the greater will be the fraction of the skeleton that is spared irradiation and the smaller will be the size of the deposits of contaminated bone. The calculations have assumed that the deposits have dimensions at least comparable to the range of the beta rays emitted, and if the dimensions are less, values of dose and dose-rate may be substantially lower than those calculated above. Therefore, for intakes limited to short periods - for example, weeks - it may well be that the maximum permissible levels of dietary contamination with strontium-90 and strontium-89 could be raised considerably above the values stated. However, more data on certain aspects of the metabolism of calcium and strontium in bone are required before any higher figures can be recommended.

Prolonging the duration of intake (so long as the daily intake of isotope does not increase) will not affect the maximum local dose-rate calculated for strontium-90. In the case of strontium-89 the maximum total dose at any site is also unlikely to be increased by prolonged intake, since the half-life of this isotope is short compared to its turnover time in bone.

CESIUM-137

The Committee considered that the maximum intake of radioactive cesium should be such that the mean radiation dose to the whole body would not in the most unfavorable case exceed 10 rad.

Since fresh milk would be the most important source of radio-cesium, young children, because of their high intake relative to their body mass, would be those at greatest risk. From the way in which cesium enters milk it can be assumed that the contamination of milk would decrease rapidly, and a value of 10 weeks has been taken for its half-period. The evidence following the Windscale accident suggests that this would be an upper limit for the half-value period of radiocesium in milk. In consequence of this and of the value assumed for the half-period in the body, it may prove that the recommended maximum values for the initial daily intake are unduly low and might safely be higher.

The initial daily intakes which would produce a dose of 10 rad to the whole body are

60 mμc at birth, 150 mμc at 6 months, and 1,150 mμc in the adult, using the following assumptions: (1) the mass of the body is taken to be 3.7 kg. at birth, 8.8 kg. at the age of 6 months, and 70 kg. in the adult; (2) uptake is assumed to be 100% in each case; and (3) a value of 20 weeks is taken for the half-period of cesium in the body although some evidence suggests that this value may be unduly high. The corresponding total intakes are 6 μc, 15 μc, and 115 μc. The maximum initial concentration in milk for children at birth and aged 6 months is about 150 mμc per liter in either case.

Limitation of the concentration of this particular radioactive material in food supplies to levels permissible for infants and children would mean that adults would receive doses of whole-body radiation which are much smaller than 10 rad.

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Radiation Protection Guides

I. PHILOSOPHY OF RADIATION PROTECTION

The setting and execution of guidelines for radiation protection are based upon an underlying philosophy in which two factors are of prime importance. First is the assumption that radiation effects follow a linear, or non-threshold dose-response relationship. There is convincing evidence, particularly insofar as the genetic effects of radiation are concerned, that there exists a non-threshold phenomenon; and although positive proof is thus far lacking, it has been deemed prudent to adopt this more conservative hypothesis in setting protection standards for large numbers of people. According to the non-threshold concept, there is no radiation dose so small that it does not involve some degree of risk. The non-threshold relationship, therefore, implies that there is no radiation protection guideline, no matter how low, which can insure absolute safety to every individual in a large population receiving the guideline dosage. However, since the magnitude of the risk is proportional to the dose received, untoward effects would become manifest at very low dose levels only if extremely large numbers of exposed individuals were observed.

The second major factor to consider is that radiation, like many other developments of modern life (such as the automobile) confers great benefit upon both society and the individual along with its risk to health. Consideration of the extent of these benefits makes a certain degree of risk acceptable. Thus, a balance must be struck in each contemplated radiation usage, in which the benefit to be gained is weighed against the anticipated risk. If the benefit outweighs the risk, the radiation is utilized so that its maximum benefit will be realized while human exposure will be maintained at the minimum consistent with deriving these benefits. The overall public health philosophy, then, is to attain maximum advantage from the use of ionizing radiation while minimizing concomitant exposure, that is, eliminating wherever possible all unnecessary exposure to radiation.

The Radiation Protection Guide (RPG) may be defined as the radiation dose which should not be exceeded without careful consideration of the reasons for so doing. In light of the non-threshold phenomenon, every effort should be made to encourage the maintenance of radiation exposures as far below the guide as practicable. Methods of estimating guides are primarily based on past experience in which individuals have been exposed to radiation for various reasons and upon animal experiments which have contributed greatly to the study of the effects of radiation. From this combined knowledge and from an understanding of the relative biological damage produced by various types of radiation, protection guides for whole-body exposure and for various organs have been recommended. These guides, of course, represent doses far below those at which any effects have thus far been observed.

II. BASIS FOR RADIATION PROTECTION GUIDES

Establishment of "safe" levels of long-term radiation dose requires knowledge of the cause-effect relationship between radiation dose and biological damage. Such damage may appear many years after initial exposure and is usually indistinguishable from the normal diseases and impairments of man. Information accumulated on this subject is, therefore, difficult to evaluate and is often controversial. Nevertheless, observations involving man and animal life have resulted in the accumulation of significant data. These include:

A. Genetic Effects

1. Studies involving fruit flies and mice
2. Hiroshima and Nagasaki populations (inconclusive)

B. Incidence of Neoplasms

1. Bone tumors in radium dial painters
2. Leukemia in radiologists
3. Thyroid carcinoma in children irradiated in infancy
4. Various neoplastic diseases, including leukemia, in patients receiving therapeutic radiation for a variety of reasons
5. Leukemia in offspring of mothers irradiated during pregnancy
6. Leukemia in survivors of Hiroshima and Nagasaki bombings

C. Life-Span Shortening

1. Studies with various animal species.
2. Radiologists vs. other physicians.

Evaluations of these observations in terms of allowable radiation dose to man is an exceedingly complex task. The National Council on Radiation Protection and Measurements (NCRP) has accepted the task and over the past 30 years has established recommendations regarding maximum permissible doses. Because of the fragmentary evidence currently available, the NCRP points out that these levels are not necessarily completely safe limits but rather levels which should carry an acceptable risk.

In 1959, the Federal Radiation Council was formed to provide a Federal policy on human radiation exposure. This organization published its first report in May, 1960. Its recommendations were essentially the same as those of the NCRP and the International Commission of Radiological Protection (ICRP). The Council suggested, however, that the terms "Radiation Protection Guides" replace the former "Maximum Permissible Doses." The newer terminology recommended by the Federal Radiation Council is used throughout this lecture outline.

III. CURRENT RECOMMENDED DOSE LIMITS

Radiation Protection Guides vary depending on whether the whole body or only a portion thereof is exposed and whether radiation workers or the general public is involved.

A. Radiation Workers

1. ACCUMULATED DOSE (EXTERNAL SOURCES)

a. For external exposure to the whole body, the maximum average dose rate should not exceed 5 rems per year. The same dose rate applies to the head and trunk, active blood-forming organs, the gonads, and the lenses of the eyes.

No occupational dose is allowed persons under 18 years of age. The accumulated dose at any subsequent age, therefore, should not exceed 5(N-18) rems where N is the age of the worker in years.

b. Generally, however, where only a single portion of the body is exposed, Radiation Protection Guide average dose rates are higher. For example, it is recommended that the average dose rate to the hands and forearms and to the feet and ankles should not exceed 75 rems per year.

2. ACCUMULATED DOSE (INTERNAL SOURCES)

a. Certain elements, upon ingestion, inhalation, etc., deposit uniformly throughout the body. Radioisotopes of these elements deliver a dose to the whole body. The Radiation Protection Guide dose rate for whole-body exposure from such radionuclides has the same limit as from external sources (i.e., 5 rems per yr.). No occupational exposure is allowed persons under 18 years of age.

b. Other radionuclides tend to localize in one or more selected body organs. Based on the essentiality of the organ to proper body function, epidemiological experience with radium, and genetic considerations, other Radiation Protection Guides have been specified for selected critical body organs.

(1) For most individual organs, it is recommended that the maximum average dose rate not exceed 15 rems per year.

(2) For the thyroid and skin, the maximum average dose rate should not exceed 30 rems per year; for the gonads, the average dose rate should not exceed 5 rems per year.

(3) For compact bone, the maximum permissible dose rate is limited to the average dose rate which would result from a body burden of 0.1 microcurie of radium. (This amount of radium would yield a dose rate of approximately 28 rems per year.)

B. General Population Groups

Recommended Radiation Protection Guides for the general population are considerably below those for radiation workers. One of the reasons for this stricter limitation on allowable dose is related to the possibility of genetic effects from radiation exposure. Because the general population contains all of the germ plasm controlling the genetic viability of the race, any mutational effects on this population would have a far greater total impact than exposure of that small segment of the population working with radiation.

Currently it is recommended that the yearly radiation exposure of individuals in general population (exclusive of natural background and the deliberate exposure of patients by dentists and doctors) should be held to one-tenth of the permissible occupational levels. Thus, for whole-body exposure of individuals in the general population, the radiation dose should not exceed 0.5 rem per year.

Exposure of the total population (this includes radiation workers and special groups, as well as the general population) presents a different problem. Here, it is necessary to make assumptions concerning the relationship between the recommended Radiation Protection Guide of 0.5 rem per year for individuals in the general population, and the average dose received by average total population groups. The Federal Radiation Council suggests the use of the arbitrary assumption that the majority of individuals do not vary from the average by a factor greater than three. Thus, they recommend the use of 0.17 rem as a Radiation Protection Guide for yearly whole-body exposure of average total population groups. This is in keeping with their recommendation that the average genetically significant dose to the total population not exceed 5 rems up to age 30 (exclusive of natural background and purposeful exposure of patients by practioners of the healing arts).

Assessment of the amount of radiation dose received by a given individual or population group requires totalling the doses received from external and internal sources. External exposures may be measured with a sufficient degree of accuracy by direct roentgen-rate monitoring procedures. Internal doses are assessed in terms of the concentration of specific radionuclides in air, water, milk, and food which may be inhaled or ingested. To enable comparison of the radioactivity concentrations measured in these various environmental phases with Radiation Protection Guides, concentration values[1] which are related to the established RPG have been derived for many radionuclides.

C. Factors Influencing Radioactivity Concentration Guides

The Radioactivity Concentration Guide is the concentration of radioactivity in the environment which is determined to result in whole-body or organ doses equal to the RPG. In calculating RCG values for a given radionuclide, the following factors must be taken into consideration:

1. INITIAL BODY UPTAKE

Large fractions of some elements are absorbed when taken into the body. In the case of certain other elements, only small fractions are absorbed in passage through the gastrointestinal tract.

Therefore, the greater retention would increase the hazard from the first group as compared with the second, other factors being equal.

When radionuclides are inhaled, unless information specific to the radionuclide is available, it is assumed, in the case of soluble compounds, that 25 percent is retained in the lower respiratory tract. From here, the nuclides move into the blood stream and a portion of each is deposited in its critical tissue within a few days. Approximately 50 percent is held in the upper respiratory tract and is swallowed. In the case of insoluble compounds, it is assumed that 12 percent is retained in the lower respiratory tract, which is usually taken as a critical organ. The remainder is eliminated by exhalation and swallowing.

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[1] Concentration values are expressed in terms of Radioactivity Concentration Guides (RCG) or Maximum Permissible Concentrations (MPC).

2. FRACTION RETAINED IN THE BODY

The rate of elimination from the blood and tissues of the body varies considerably for different elements or compounds. The time required for one-half of the original quantity of radioactive material to be removed from the body by biological processes is called the biological half-life.

Some materials in the blood stream are eliminated rapidly from the body whereas large fractions of others remain in the body organs. For example, radium, plutonium, and strontium are deposited in the bone where the rate of turnover is very slow; i.e., the biological half-life is many years. Radioisotopes of these elements are much more hazardous than those of carbon, sodium, and sulfur which have biological half-lives of a few days or weeks. The principal biological methods of elimination of radionuclides from the body are the urine, feces, exhalation, and perspiration. Usually elimination is much more rapid before the radionuclide is translocated from the body to a more permanent area, such as the bone. This time is usually from a few days to a few weeks. After the initial period, the elimination rate becomes more nearly exponential, and the application of the term "biological half-life" has more meaning.

3. ORGAN OR TISSUE IN WHICH RETAINED[2]

a. Radiosensitivity - Certain body organs or tissues are more radiosensitive than others. For example, the lymphatic tissue and bone-marrow are much more radiosensitive than muscle or nerve tissue. Therefore, in equal concentrations, an element like plutonium is more hazardous than uranium because the plutonium concentrates in the most sensitive part of the bone, whereas the uranium goes to other portions of the bone, to the kidneys, and to other relatively insensitive organs.

b. Size - For a given number of microcuries of a radionuclide in a critical organ, the smaller the organ the greater the concentration and the greater the dose delivered to the critical tissue. Iodine presents a much greater problem than sodium, since the iodine is very selectively absorbed in a much smaller organ, the thyroid gland, whereas sodium is rather uniformly distributed throughout the whole body. In many cases the radionuclide is deposited in a large organ but localized in a small portion of that organ, so that, in effect, the mass of the critical tissue may become very small.

c. Essentiality - Some organs are either not essential to the body function, or, when they are damaged or removed, special steps can be taken to supplement or compensate for their reduced function. For these reasons damage in some cases to the bone-marrow, kidneys, eyes, etc., may represent a greater hazard than equal tissue damage to the thyroid gland.

4. PHYSICAL PROPERTIES OF THE RADIONUCLIDE

a. Type and Energy of Radiation - The hazard is proportional to the relative biological effectiveness or quality factor of the radiation; e.g., alpha radiation is more damaging than beta radiation for a given energy of radiation. As the energy of the radiation is increased, the damage also increases.

b. Half-Life - The shorter the physical or radioactive half-life of a radionuclide, the less is the biological hazard. The radioactive half-life and the biological half-life may be combined into a single "effective" half-life by means of the formula:

$$T_{eff} = \frac{(T_r) \times (T_b)}{T_r + T_b}$$

D. Calculations of Radioactivity Concentration Guides

As an example of the approach used in determining RCG values, the case of cesium-137 is illustrated.

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[2] In certain instances, an organ of the body, such as the GI tract or lung, may receive a significant dose due to the mere presence of the radionuclide in material inhaled or ingested. Under these circumstances, the organ so exposed (even though not absorbing the radionuclide) may become the "criticial" organ.

1. The element cesium is distributed rather uniformly throughout the body. Therefore, an RPG for the radiation worker of five rems per year is selected for any radioisotope of this element.

2. Experimental and theoretical studies have shown that the presence in the body of 30 microcuries of ^{137}Cs will yield a whole-body dose rate of five rems per year. This quantity, 30 microcuries, is referred to as the "maximum permissible body burden" for ^{137}Cs.

3. If, however, 30 microcuries of ^{137}Cs were deposited within the body, they would not remain there long because of biological elimination and radioactive decay. Therefore, a certain amount could be ingested continually without exceeding the maximum permissible body burden.

4. A "standard man" consumes approximately 2200 milliliters of water per day. Approximately one-half of this is ingested during the working hours. If the daily intake of ^{137}Cs via drinking water is to be limited such that the "maximum permissible body burden" will not be exceeded (and the average yearly radiation worker whole-body dose rate not exceed five rems), then the concentration of this nuclide in drinking water must not exceed 4×10^{-4} microcuries per milliliter. This value, 4×10^{-4} Ci/ml, is the Radioactivity Concentration Guide (RCG) for ^{137}Cs in drinking water for consumption by radiation workers, based on an eight-hour per day, 40-hour work week for a radiation worker.

In a similar manner, it can be shown that an average concentration of 6×10^{-8} Ci/ml soluble ^{137}Cs in air in the working environment would result in a worker receiving a whole-body dose rate of five rems per year.

E. Standardization of Calculations

When efforts were first made to establish permissible body burdens and Radioactivity Concentration Guide values for the various radionuclides, it became evident that it would be difficult, if not impossible, to compare suggested values from the different laboratories unless all used the same basic assumptions relative to the average man. Most of the calculations were based on the same fundamental physical assumptions relative to the energy schemes and radioactive half-life values, but each person making these calculations used his own preferred values for the mass and effective radius of the body organs, the rates of ingestion and inhalation, elimination rates, etc. This difficulty was recognized at several major conferences. As a consequence certain characteristics of the so-called "standard man" were agreed upon.

F. Graded System of Actions

It was felt by the Federal Radiation Council that a commitment to the single values represented by the Radioactivity Concentration Guides might prove arbitrary and inflexible, and not provide adequate guidance for taking assessment and control actions appropriate to the risk involved. Therefore, the Council's Report No. 2 introduced the concept of graded scales of RANGES of action in which average daily intake of a radionuclide by samples of exposed population groups are listed in three ranges. These ranges apply to certain selected radionuclides of health significance, namely, radium-226, strontium-89, strontium-90, and iodine-131. In general, the single radioactivity concentration guide equivalent corresponds to the upper limit of RANGE II. For intakes in RANGE I, the Council guideline recommends periodic, confirmatory surveillance as necessary; for RANGE II, quantitative surveillance and routine control is indicated; and for RANGE III, the Council advises evaluation and application of control measures as necessary.

G. Protective Action Guides

All of the foregoing guidelines are predicated upon the more or less constant release of low-level radioactivity into the environment from the routine uses of radiation, and assume continuous radionuclide intake by the population. Control, then, is based primarily at the source. There are cases, however, in which the contamination of the environment might be accidental or unforeseen, producing contamination which is transient and not likely to recur; these might include reactor incidents which result in relatively high but temporary local radioactivity levels, for example. In cases of this kind, the "contaminating event" would not occur on a regular basis, and control, or protective action, might be based upon limiting or changing the intake of certain contaminated foods by the population. However, the impact of such measures upon the community which they are designed to benefit requires careful consideration by responsible authorities to insure that the benefit of the action taken is not outweighed by its other effects. To deal with this kind of situation, the Council, in its Reports No. 5 and No. 7, introduced the Protective Action Guide concept. The PAG is defined as the projected absorbed dose to individuals in the general population which would warrant protective action following a contaminating event. It is assumed that the corresponding projected dose to a suitable sample of the exposed population would be one-third of the PAG. These guidelines have, thus far, been established for iodine-131, strontium-90, and cesium-137. It should be noted that a decision to take action to limit a community's intake of an important basic food item containing radionuclides involves a balancing of the health benefits to be attained against the undesirable features of the protective action, such as disruption of dietary habits and nutritional needs. It follows, then, that control actions could be employed at dose levels above or below the PAG, depending upon the degree of total impact which the action has upon the community.

V. SUMMARY

Based on current information, Radiation Protection Guides for radiation dose have been recommended. These levels are subject to modification as more knowledge is gained. In view of their status and the possibility that any radiation dose may be damaging, it is well to recall the definition of the Radiation Protection Guide as that radiation dose which should not be exceeded without careful consideration of the reasons for doing so. Every effort should be made to encourage the maintenance of radiation doses as far below the Guide as practical.

Table 1 summarizes the current recommendations of the ICRP and the Federal Radiation Council.

Table 1. Radiation Protection Guides

Type of Exposure	Condition	Dose[1] (rem)
Radiation worker:	Accumulated dose	Five times number of years beyond age 18
(a) Whole body, head, and trunk, active blood-forming organs, gonads, or lens of eye	13 weeks	3
(b) Skin of whole body and thyroid	Year	30
	13 weeks	10
(c) Hands and forearms, feet and ankles	Year	75
	13 weeks	25
(d) Bone	Body burden	0.1 µCi of ^{226}Ra or its biological equivalent
(e) Other organs	Year	15
	13 weeks	5
Population:		
(a) Individual	Year	0.5 (whole body)
(b) Average	30 years	5 (gonads)

[1] Minor variations from other recommendations are not considered significant in light of present uncertainties.

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The Correlation of Exposure Dose and Absorbed Dose

I. INTRODUCTION

The biological injury which ionizing radiations are capable of producing is due strictly to the energy which is absorbed by body tissues. If exposed to x- or gamma rays, the body suffers no injury from those photons which pass through it without interaction. Since the degree of biological injury is related directly to the number of interactions which do occur, it becomes a matter of extreme importance to be able to measure or calculate the number of such interactions either by direct or indirect means.

For reasons which will be discussed, the ability of a beam of x- or gamma-ray photons to produce a given number of ionized air molecules is used to describe the "strength" of that particular photon beam.

II. THE ROENTGEN UNIT

When a beam of photons has interacted with air molecules at standard temperature and pressure to produce, through primary and secondary ionizations, 2.083×10^9 ion pairs per cubic centimeter of air, then by definition, the air has been exposed to an x- or gamma-photon beam producing an exposure dose of 1 roentgen.*

Note that the roentgen is not basically a measure of absorbed energy but is merely a number; i.e., 2.083×10^9 ion pairs per cm^3 of standard air. However, since it is known approximately how much energy is required to produce a single ion pair in air, it is possible to calculate the total absorbed energy associated with the production of 2.083×10^9 ion pairs in air. On this basis, the amount of energy absorbed (or dissipated) within a cubic centimeter of air is equal to $0.1135\ ergs/cm^3$ of standard air or 87.7 ergs per gram of standard air. (This result assumes the ionization potential** of air to be equal to 34 electron volts).

To measure the "strength" of an x- or gamma-ray beam, a volume of air is "placed" in the beam path. The ion pairs formed in this volume of air by the photons passing through it, and by the secondary electron interactions, can then be attracted to electrodes. (Fig. 1) As each ion pair consists of one positively charged ion and one negatively charged ion, the ions are attracted to the oppositely charged electrodes and result in an electrical stream. It is this electrical stream which becomes a means for measuring the number of ion pairs and therefore measures the "air exposure dose"; i.e., the roentgens.

In Figure 1, the "volume of air" is indicated by the shaded area in the center of the

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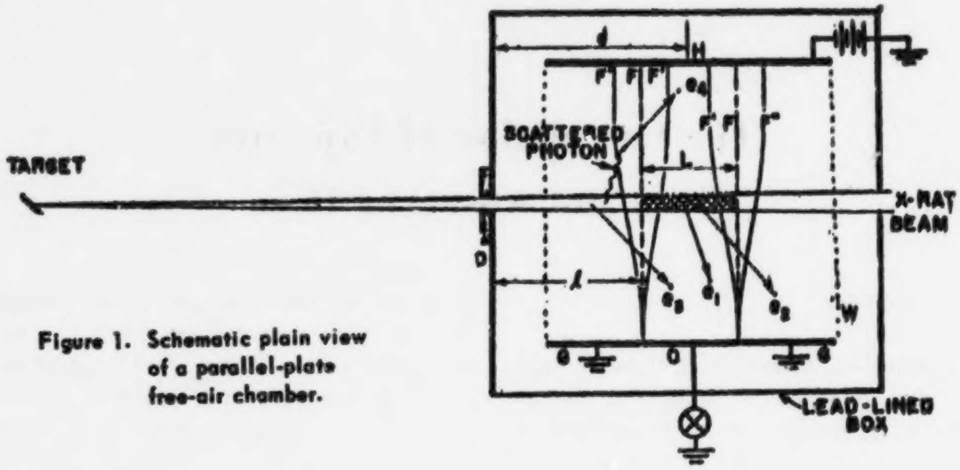
*One roentgen is an exposure dose of x- or gamma radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of electricity of either sign.

**Ionization potential is the electrical energy necessary to separate one electron from an atom, resulting in the formation of an ion pair.


TARGET
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LEAD-LINED BOX

Figure 1. Schematic plain view of a parallel-plate free-air chamber.

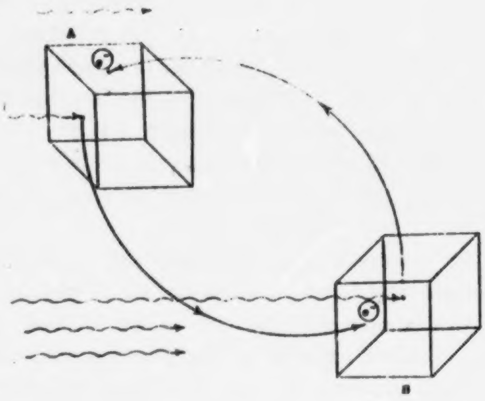

Figure 2

Electronic equilibrium between two cubes of air irradiated by a uniform photon field

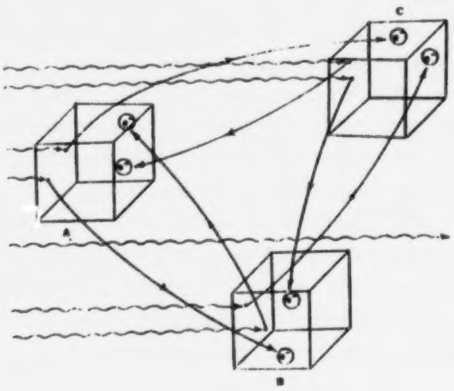

Figure 3

Electronic equilibrium between three cubes of air irradiated by a uniform photon field box. The electrodes (termed "collecting electrodes") are designated H and C. The design of such measuring chambers, which are called "parallel-plate, free-air ionization chambers", must take into consideration many complicated factors, not the least of which are the dimensions of the "volume of air", from which the ions are collected which must exceed the range of the most energetic secondary electrons formed. In addition, the condition of "electronic equilibrium" must be satisfied.(2)

III. ELECTRONIC EQUILIBRIUM

In Figure 2 are pictured two cubes of air both of which are in a uniform field of photonic radiation. In each cube, ionizations of air molecules are taking place and secondary electrons are assumed to be dissipating their energy both inside and outside the cubes. The concept of electronic equilibrium states that if an electron formed in cube A has a likelihood of dissipating some of its energy in cube B, then the same likelihood exists that an electron formed in cube B will dissipate the same amount of energy in cube A.

This concept can be extended to include any similar cube of air, as depicted in Figure 3, where electronic equilibrium is shown to exist between three cubes of air. Carrying this concept of its completion, it is possible to visualize that all such cubes of air, which would total to give the entire volume in the radiation field, would be in electronic equilibrium.

This concept is important because electronic equilibrium can exist not only between reciprocal volumes of air but also between a volume of air and some other absorbing medium; e.g., the "air-equivalent" wall of a thimble chamber. It is this fact which enables one to measure the ionization taking place in a volume of air located within a medium such as tissue and thereby to make some statement of the amount of energy being absorbed by that tissue.

IV. EXPOSURE DOSE

The roentgen, or exposure dose, has been defined strictly in terms of the number of ion pairs formed within a given volume of air. This volume of air might be termed the "sensitive volume", since it is from this volume that the ion pairs are collected for measuring the exposure dose. Note that in the free-air ionization chamber, the electronic equilibrium exists between the "sensitive volume" (i.e., the "collecting volume") and a much larger air volume within which the sensitive volume is contained. It should be remembered that the roentgen is an exposure dose of x- or gamma radiation based upon ionizations in air, but that it does not express a quantity of ionization; it is not a unit of ionization, nor is it an absorbed dose in air.

In media other than air, the x- or gamma ray photons interact with the atoms, forming primary and secondary electrons which dissipate their energy in the medium. The quantity of ionization is normally related to the absorbed dose and is expressed in the unit of absorbed dose; i.e., the rad.

The ionization in the medium may be related to the absorbed dose by application of the Bragg-Gray theory.

V. BRAGG-GRAY THEORY

If an ionization chamber with a sufficiently small volume has a wall material thicker than the range of the most energetic secondary electrons produced in the medium of interest, a relationship can be derived between the true quantum energy absorption in the wall material and the ionization in the air, or in any other gas filling the chamber.

For the above statement to be true, certain conditions must be met:

A. The cavity must be of such dimensions that only a small fraction of the particle energy is dissipated in it. This means also that only a small fraction of the particles contributing to the ionization will enter the cavity with a range smaller than the cavity dimensions.

B. Direct absorption by photonic radiation by the air in the chamber should contribute only a negligible proportion of the total ionization in the chamber - a requirement usually satisfied if the chamber, or cavity, complies with the first criterion.

C. The cavity must be surrounded by an "equilibrium thickness"* of the solid medium so that all particles crossing it originate in the medium.

D. The energy dissipation by the ionizing particles must be sensibly uniform throughout the volume of the medium immediately surrounding the cavity and contributing to electronic equilibrium.

If the above conditions are fulfilled, the energy, E_m, in ergs absorbed per gram of material (tissue) is related to the ionization per gram of gas, J_m by the equation:

$$E_m = J_g W s_m$$

where:

J_g = the number of ion pairs formed per gram of gas

W = the average energy in ergs required in forming each ion pair

s_m = the ratio of the mass-stopping power of the medium to that of the cavity gas for these ionizing particles; i.e., the secondary electrons.

The value of W, in air, for x- or gamma radiation is about 5.4×10^{-11} ergs. This corresponds to an ionization potential of air equal to 34 electron volts.

The factor, s_m, can be expressed as:

$$s_m = \frac{N_m \, {}_eS_m}{N_g \, {}_eS_g}$$

where:

N_m = the number of electrons per gram of medium (in this case, tissue)

N_g = the number of electrons per gram of gas

${}_eS_m$ = the stopping power for electron for the medium or wall material

${}_eS_g$ = the stopping power per electron for the gas (in most cases, air)

In effect, the factor, s_m states how much more frequently ionization will occur in the medium compared to the gas in the cavity; i.e., the "sensitive volume" within the medium. Therefore; measuring J_g (the ionizations occurring per unit mass of gas in the "sensitive volume") plus a knowledge of S_m and W enables one to determine the absorbed dose in the tissue. Methods are available for calculating ${}_eS_m$ and ${}_eS_g$.(3)

Figure 4 illustrates how the ratio of ${}_eS_m/{}_eS_g$ varies with the atomic number (Z) of the medium in the case of secondary electrons produced by RaB and RaC gamma rays.

For x- or gamma rays of different energies, a different curve would result.

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*The thickness which will just result in electronic equilibrium. It is approximately equal to the range of the most energetic secondary electron.

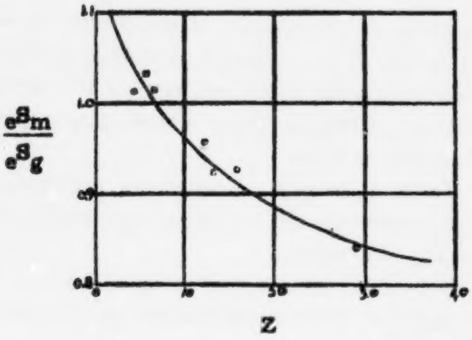

Figure 4

VI. ABSORBED DOSE IN AIR DUE TO AN EXPOSURE DOSE OF 1 ROENTGEN

It is convenient at this point to show how the energy absorbed by air can be calculated, following an exposure dose of 1 roentgen.

As defined, 1 roentgen = 2.082×10^9 electrons/cm^3 of air at S.T.P.* Dimensional analysis leads us directly to what we seek. This is carried out as follows:

By definition:

$$1 \text{ r} = 1 \text{ esu/cm}^3 \text{ of air}$$

$$= \frac{2.082 \times 10^9 \text{ electrons (or ion pairs)}}{0.001293 \text{ gms of air}}$$

$$= \frac{1 \text{ esu}}{0.001293 \text{ gms of air}}$$

Thus,

$$\frac{1 \text{ esu}}{0.001293 \text{ gm air}} \times 2.082 \times 10^9 \frac{\text{electrons}}{\text{esu}} \times \frac{34 \text{ e.v.}}{\text{ion pair}} \times 1.602 \times 10^{-12} \frac{\text{ergs}}{\text{e.v.}} \times \frac{1 \text{ rad}}{100 \text{ erg/g}} = 0.87 \text{ rads**}$$

Thus, if we call the absorbed dose in air, D(air), the following equation can be written.

$$D(\text{air}) = 0.87 \text{ R rads}$$

where:

D(air) = the absorbed dose in rads

R = the exposure dose in roentgens

The absorbed dose in ergs is obtained by multiplying D(air) by 100. Thus, the absorbed dose in air due to an exposure dose of 1 r is 0.87 R × 100 = 0.87 × 1 × 100 = 87 ergs per gram of air.

Note that the equation

$$D(\text{air}) = E_m = J_g W s_m$$

could have been applied directly to solving the above problem. In this case, the ratio

$$s_m = \frac{N_m \, {}_eS_m}{N_g \, {}_eS_g}$$

would be equal to 1, since the medium is identical to the gas. This would simplify the equation to

$$D(\text{air}) = E_m = J_g W$$

J_g by definition is 1.61×10^{12} ion pairs/gm of air and W is 5.4×10^{-11} ergs per ion pair.

substituting:

$$D(\text{air}) = E_m = 1.61 \times 10^{12} \frac{\text{i.p.}}{\text{gm air}} \times 5.4 \times 10^{-11} \frac{\text{ergs}}{\text{i.p.}} = \frac{87 \text{ ergs}}{\text{gm air}}$$

VII. ABSORBED DOSE IN TISSUE

It has been shown that the energy absorbed in a medium is directly related to the ratio of the electron-stopping power of the medium to that of air; e.g. ${}_eS_m/{}_eS_g$.

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*S.T.P. = Standard temperature and pressure

**1 rad is defined as 100 ergs of energy absorbed per gram of any absorbing medium

It is also true that the ratio of the dose absorbed in the medium, D(med), to the dose absorbed in air, D(air) is directly proportional to the ratio of the energy absorption coefficient of x- or gamma rays in the medium and in air. This can be stated simply as:

$$\frac{D(\text{medium})}{D(\text{air})} = \frac{(m^{\mu}en)\ \text{medium}}{(m^{\mu}en)\ \text{air}}$$

where:

D(medium) = dose absorbed by the medium (in rads or ergs)

D(air) = dose absorbed by the air (in ads or ergs)

$(m^{\mu}en)$ medium = the mass energy absorption coefficient for the medium

$(m^{\mu}en)$ air = the mass energy absorption coefficient for the air.

Using the relationship previously derived,

$$D(\text{air}) = 0.87\ R\ \text{rads},$$

it is possible to substitute in the above equation to obtain

$$D(\text{medium}) = 0.87\ R \times \frac{(m^{\mu}en)\ \text{medium}}{(m^{\mu}en)\ \text{air}}$$

where D(medium) is given in rads.

One can define a function, f, which is the absorbed dose in rads per roentgen of exposure dose, whereby

$$D(\text{medium}) = f\ R\ \text{rads}$$

or,

$$f = \frac{D(\text{medium})}{R} = \frac{0.87\ (m^{\mu}en)\ \text{med}}{(m^{\mu}en)\ \text{air}}$$

$$= \frac{\text{rads}}{\text{roentgen}}$$

Because the extent to which x- or gamma-ray photons interact with air or tissue is a function of the energy of the photon as well as of the type of tissue, a different f-value exists for each photon energy and for various kinds of tissues. These values are experimentally derived.

Table I is reproduced from reference 1 and shows how the f-value varies with photon energy and tissue.

Note that, except for the constant, 0.87, f is merely the ratio of the energy absorption coefficient for the medium and air. The energy absorption coefficient is $(m^{\mu}en) = m\tau + m^{\sigma}a + m^{K}$ for air or medium, as the case may be. In this equation $m\tau$ is the true photoelectric mass-absorption coefficient, $m^{\sigma}a$ is the true Compton mass-absorption coefficient, and m^{K} is the true pair-production mass-absorption coefficient. (Note: The mass-absorption coefficient for x- or gamma rays is defined by the equation

$$\frac{I}{I_o} = e^{-m^{\mu}\rho}$$

where:

I_o = the incident photon flux

I = the exit photon flux

x = the thickness of the shield through which the photons pass

m^{μ} = the mass absorption coefficient

ρ = the density of the absorber

The value of m^{μ} is a function of the photon energy and differs for each absorber material. (Radiological Health Handbook, page 142).[4] However, the mass-absorption coefficient does not represent exactly the fraction of the photon flux being converted into absorbed energy since part of the incident beam is scattered by Compton scattering out of the path of the incident beam without yielding all its energy to the medium. Correction must be made for this by using

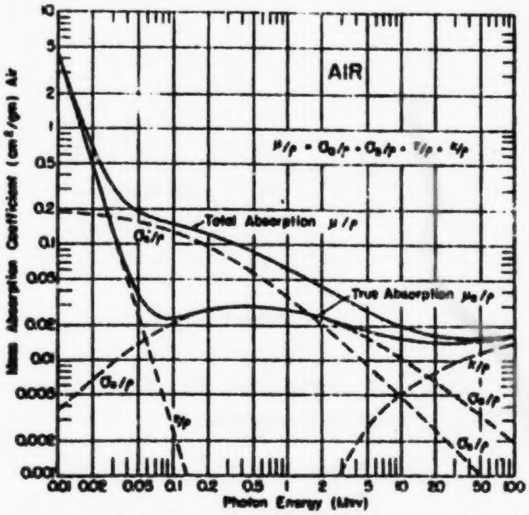
Table 1· Values of the Mass Energy-Absorption Coefficients and the Factor f

Photon energy	Mass energy-absorption coefficient, (μ_{en}/ρ) cm²/g															$f=0.87\cdot\left[\frac{(\mu_{en}/\rho)_{medium}}{(\mu_{en}/\rho)_{air}}\right]$		
	H	C	N	O	Na	Mg	P	S	A	K	Ca	Water	Air	Bone	Muscle	Water/Air	Bone/Air	Muscle/Air
Mev																		
0.010	0.00992	1.94	3.42	5.50	15.4	20.9	40.1	49.7	62.0	77.0	89.8	4.89	4.66	19.0	4.96	0.92_0	3.58	0.93_3
.015	.0110	0.517	0.916	1.49	4.43	6.09	11.9	15.2	19.4	24.6	28.9	1.32	1.29	5.89	1.36	$.89_7$	4.00	$.92_5$
.020	.0133	.203	.300	0.587	1.77	2.47	5.00	6.41	8.31	10.5	12.5	0.523	0.516	2.51	0.544	$.88_7$	4.27	$.92_3$
.030	.0186	.0592	.102	.163	0.482	0.684	1.45	1.85	2.46	3.12	3.75	.147	.147	0.743	.154	$.87_7$	4.43	$.91_9$
.040	.0230	.0306	.0465	.0700	.194	.274	0.570	0.731	0.974	1.25	1.52	.0647	.0640	.305	.0677	$.88_7$	4.16	$.92_0$
.050	.0270	.0226	.0299	.0410	.0996	.140	.282	.361	.454	0.626	0.764	.0394	.0384	.158	.0409	$.90_6$	3.61	$.93_4$
.060	.0305	.0203	.0244	.0304	.0637	.0645	.166	.214	.284	.367	.443	.0304	.0292	.0979	.0312	$.91_8$	2.94	$.93_7$
.080	.0362	.0201	.0218	.0239	.0369	.0456	.0780	.0971	.124	.156	.191	.0253	.0236	.0520	.0255	$.94_0$	1.93	$.94_8$
.10	.0406	.0213	.0222	.0232	.0268	.0334	.0500	.0599	.0725	.0909	.111	.0252	.0231	.0386	.0252	$.95_7$	1.47	$.95_7$
.15	.0485	.0246	.0249	.0252	.0258	.0275	.0315	.0351	.0368	.0433	.0488	.0278	.0251	.0304	.0276	$.97_1$	1.06	$.96_4$
.20	.0530	.0267	.0267	.0271	.0265	.0277	.0292	.0310	.0302	.0339	.0367	.0300	.0268	.0302	.0297	$.96_7$	0.95_1	$.97_2$
.30	.0573	.0288	.0289	.0289	.0278	.0290	.0290	.0301	.0278	.0304	.0319	.0320	.0288	.0311	.0317	$.97_2$	$.94_7$	$.96_5$
.40	.0587	.0295	.0296	.0296	.0283	.0295	.0290	.0301	.0274	.0299	.0308	.0329	.0296	.0316	.0325	$.97_3$	$.93_4$	$.96_3$
.50	.0589	.0297	.0297	.0297	.0284	.0293	.0288	.0300	.0271	.0294	.0304	.0330	.0297	.0316	.0327	$.97_4$	$.93_3$	$.96_6$
.60	.0588	.0296	.0296	.0296	.0283	.0292	.0287	.0297	.0270	.0291	.0301	.0329	.0296	.0315	.0326	$.97_3$	$.93_1$	$.96_6$
.80	.0573	.0286	.0289	.0289	.0276	.0285	.0280	.0287	.0261	.0282	.029	.0321	.0289	.0306	.0318	$.97_4$	$.92_9$	$.96_5$
1.0	.0555	.0279	.0280	.0280	.0267	.0275	.0270	.0280	.0252	.0272	.0279	.0311	.0280	.0297	.0308	$.97_4$	$.92_7$	$.96_4$
1.5	.0507	.0255	.0255	.0255	.0243	.0250	.0245	.0254	.0228	.0247	.0253	.0283	.0255	.0270	.0281	$.97_3$	$.92_6$	$.96_4$
2.0	.04	.0234	.0234	.0234	.0225	.0232	.0228	.0235	.0212	.0228	.0234	.0260	.0234	.0248	.0257	$.97_4$	$.92_9$	$.96_4$
3.0	.03	.0204	.0205	.0206	.0199	.0206	.0204	.0210	.0193	.0208	.0213	.0227	.0205	.0219	.0225	$.97_1$	$.93_7$	$.96_5$
4.0	.0351	.0184	.0186	.0187	.0184	.0191	.0192	.0199	.0182	.0199	.0204	.0205	.0186	.0199	.0203			
5.0	.0316	.0170	.0172	.0174	.0173	.0181	.0184	.0192	.0176	.0193	.0200	.0190	.0173	.0186	.018			
6.0	.0288	.0160	.0162	.0166	.0166	.0175	.0179	.0187	.0175	.0190	.0198	.0180	.0163	.0178	.017			
8.0	.0249	.0145	.0148	.0154	.0158	.0167	.0175	.0184	.0172	.0190	.0197	.0165	.0150	.0165	.0163			
10.0	.0222	.0137	.0142	.0147	.0154	.0163	.0174	.0183	.0173	.0191	.0201	.0155	.0144	.0159	.0154			

the true energy mass-absorption coefficient rather than the total mass-absorption coefficient. Figures 5 and 6 show the "total" and "true" mass-absorption coefficient for air and water as a function of photon energy. In addition, the contribution from photoelectric interaction, Compton interaction and pair-production is shown).

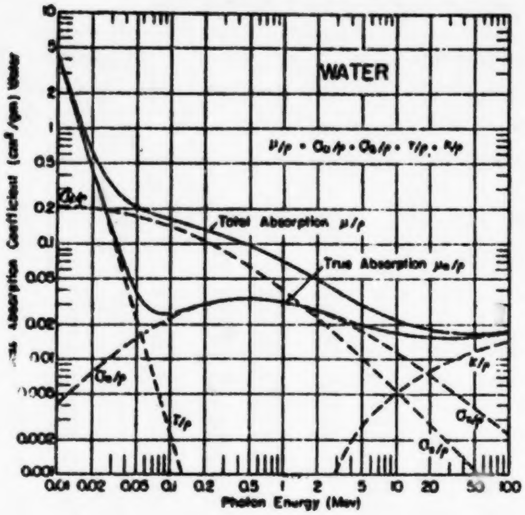
VIII. THE CALCULATION OF ABSORBED DOSE

The foregoing discussion has demonstrated that if certain parameters are known, the absorbed dose in rads can be calculated once the exposure dose in the medium has been measured. In tissue, the relationship between the exposure dose in roentgens and the absorbed dose in rads, for cobalt-60 gamma rays, is shown in Figure 7.



Mass absorption coefficients for air as a function of photon energy. The density of air is p-0.001293 gm/cm^3

Figure 5



Mass absorption coefficients for water as a function of photon energy

Figure 6

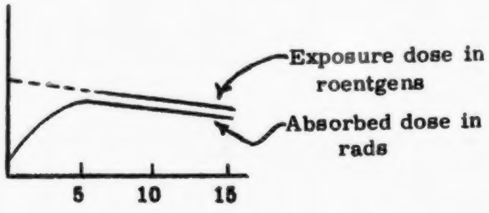


Figure 7

Figure 7 emphasizes the direct relationship of rads to roentgens

Illustration of the use of f-values

A small ionization chamber with an air-equivalent wall is placed in muscle tissue at a suitable depth and exposed to a 0.1 Mev photon beam. An exposure dose of 1 roentgen is noted. What is the tissue-absorbed dose

The steps to be followed are these:

Step 1: The dose to the wall of the ionization chamber must be calculated using the formula,

$$D_{(\text{wall})} = 0.87\ \text{R rads}$$

where:

R = esu per cc of air in the chamber

Step 2: The dose to the tissue is calculated using the formula,

$$D_{(\text{tissue})} = \frac{0.87\ \text{R}\ (m^{\mu}\text{en})\ \text{tissue rads}}{(m^{\mu}\text{en})\ \text{air}}$$

therefore,

$$D_{(\text{tissue})} = f \times \text{R rads}$$

Referring to Table 1, the f-value for muscle tissue/air for a 0.1 Mev photon is 0.95.

Substituting,

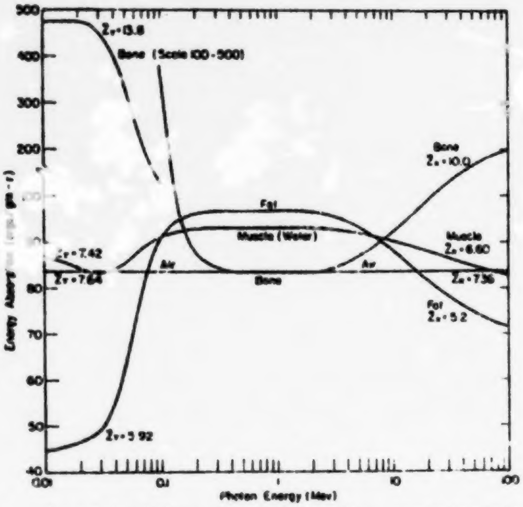
$$D_{(\text{tissue})} = 0.95 \times 1 = 0.95\ \text{rads}$$

The energy absorbed at the point of measurement is 95 ergs/gram.

IX. ABSORPTION OF ENERGY BY BIOLOGICAL MATERIALS

It has been shown that the absorbed dose can be calculated provided the number of ion pairs formed in the sensitive volume, the number of electrons per unit mass of medium and gas, and the electron stopping powers of the medium and gas are known. (See Section V). Very important to such a calculation is knowledge of the average or effective atomic number, $\overline{Z}$, of the medium of interest (when various tissues are being studied), since the amount of energy deposited per unit path length by a secondary electron is a function of the atomic number of the medium as well as the energy of the electron itself.

How the energy deposited varies with atomic number and photon energy is shown in Figure 8.



Energy absorbed per gram roentgen for bone, muscle, fat, and air function of the photon energy

Energy absorbed per gram roentgen for bone, muscle, fat, and air as a function of the photon energy.

Figure 8

NOTE: The above curves assume the ionization potential of air to be 32.5 electron-volts.

X. CONCLUDING REMARKS

This presentation is an abbreviation of an admittedly complex subject. Important points have been omitted for the sake of simplicity and brevity. For example, the discussion of electronic equilibrium did not mention that equilibrium would exist in a medium under irradiation only if the intensity and spectrum of the x- or gamma-ray beam were unchanged (i.e., were constant) throughout a region extending in all directions from the volume of interest to a point a distance at least as great as the maximum range of the electrons generated by the radiation. Also, electronic equilibrium would require that the energy absorption coefficient and stopping power be constant in the medium throughout the same region.

Similarly, the limitations of the instruments used to measure the exposure dose were not discussed. The ideal "air-wall" chamber has not been devised, for there is no solid with the same atomic composition as atmospheric air. Familiarity with these limitations can be gained by reading such a basic book as reference 3 of the bibliography.

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Some Considerations in Evaluating Radionuclide Intake

I. INTRODUCTION

The assessment of the health hazard associated with environmental radioactive contaminants requires knowledge of the intake of specific nuclides by man. The food chain forms the main route of entry of these radionuclides. Although predictions of the levels of specific radionuclides in man or his diet, may be made on the basis of monitoring the physical environment, such predictions can at best give only a rough approximation. Thus, if more accurate evaluation is desired, direct measurement of the human body or diet is necessary.

The measurement of the levels of activity in the diets of relatively small selected population groups (on an established statistical basis) may provide a method for estimating the average intake of radionuclides of larger populations. However, the applicability of such data to extrapolation to larger population groups is highly dependent on the method of sampling and the basic sampling design. Many problems in sampling arise because of wide variations in diet in different geographical areas and different socio-economic groups of a population. Thus, in planning a study of total radionuclide intake, one must consider these factors in light of the basic objectives of the study.

The purpose of this lecture is to discuss some of the factors that must be considered in designing a program for the evaluation of radionuclide intake.

II. GENERAL SURVEYS

The primary objective of the general survey is to provide knowledge of the intake of radionuclides in order to estimate the dose to which a population group is subjected. Surveys of natural radioactivity provide one standard against which increases in exposure can be judged. Surveys of the intake of both man made and natural radionuclides will provide information from which national policy decisions can be made with regard to radioactivity levels in the environment. Such information enables regulatory agencies to comply with their statutory responsibility to safeguard the health of the public.

The selection of a suitable survey design is determined by the objectives of the survey and the means which are available to execute it. These objectives also prescribe the nature and precision of the information required. If the only objective is to compare the existing levels with those considered acceptable, the precision is governed by the magnitude of the acceptable level. When, however, it is desired to investigate variations in dietary levels from place to place, or in time, the required precision will be greater. Adequate sampling of the large number of food items comprising the diet in many cases is prohibitive from the standpoint of cost. Consequently, more attention has been paid to the sampling of one indicator, milk, which is an important contributor not only of calcium and strontium-90, but also of other significant fission products.

General surveys are concerned with estimation of the content of radionuclides in the diet of the general population. They take into account contributions of a particular radionuclide to the average diet from all sources. These surveys provide a base with which the content of a radionuclide in the diet of a special group can be compared.

In designing general surveys the choice of sampling station is extremely important. The type of unit from which samples should be collected, e.g., farms, processing plants, shops or markets, depends on the food to be sampled and on the objectives of the survey. Thus, if the objective is simply to monitor intake, all analyses should be made on processed food. If on the other hand, one is attempting to relate dietary levels with other environmental conditions, raw or non-processed food would be of greater interest.

A. Total Diet Composite

The analysis of representative composite samples of a complete diet permits the estimation of total radionuclide intake. This method can be used with success in kitchens of institutions, but care must be taken to estimate the validity of extrapolation to larger populations.

An example of this type survey is the Public Health Service - Institutional Food Sampling Program. This program has been set up with the objective of determining total Sr^{90} and Ra^{226} in the diet of institutionalized children of 6 - 16 years of age in each of eight cities. A single composite sample consisting of a total diet equivalent, of 3 meals per day plus snacks for seven consecutive days is collected monthly at each institution.

An alternate method for this type of survey is to sample the stock of local food shops and then compose a diet on the basis of food consumption data. When it is desired to apply the results to the general population, sampling must be repeated in many areas. An advantage in sampling food from local stock is that this food is currently being consumed in the area and the delays between harvest and consumption are taken into account.

The disadvantages of this survey method are (1) samples may provide a biased estimate of intake when considering the general population and (2) origin of the food may be unknown.

B. Total Diet - Individual Food Components

In order to identify the more important foods that contribute radioactivity to the diet, the components must be analyzed separately. Dietary components may be analyzed individually or as groups of related foods. Typical groups are as follows: milk and milk products, cereal and cereal products, meats, fish, marine products, root vegetables, green leafy vegetables, dried legumes, nuts, fruits, and beverages. Sampling within groups is restricted only to the foods which are normally consumed in sufficient quantities to contribute significantly to the total intake.

An example of this type of study is the Tri-City Study conducted by the U.S. Atomic Energy Commission. The principal objectives of this survey are the determination of the average dietary intake of Sr^{90}, Ra^{226} and Ca for the populations of 3 metropolitan areas as a function of time, and the identification of the principal contributors of Sr^{90}, Ra^{226} to the diet. The U.S. Department of Agriculture Food Consumption Data (1) have been utilized in arriving at a food purchase plan. Dietary components are grouped into 19 categories. Sr^{90} in the total diet is obtained by summing the contributions from each category.

C. Major Dietary Contributors For Future Predictions

The major objective of this type of survey is to make correlative studies of the levels of radionuclides in foods and in the environment in order to provide information for the prediction of future levels in food from environmental measurements. This requires that individual foods be sampled and their sources identified.

There are essentially 2 choices to be made in determining where the sample should be collected. (1) Samples collected at the farm provide an excellent means of carrying out studies intended to supply information on the mechanism of contamination transfer between the environment and the food item. However, it is generally difficult to achieve a representative sample of the total production and this limits the reliance one can place upon the predicted levels. (2) Samples taken at a central collection point offers the possibility of obtaining mean values representative of total production in any given area. Milk depots are examples of such centers. The Raw Milk Sampling Program of the Public Health Service is an example of this type of program. Monthly samples of raw milk are collected from specified milksheds serving large urban populations in different regions of the United States. Analysis of samples collected in this manner provides valuable general information regarding the factors influencing the levels of radionuclides in milk as well as some notion as to the radionuclide intake for the various population groups.

III. CRITERIA FOR SELECTION OF FOODS

The quantity of radioactivity in a diet is the sum of the amounts contributed by the individual food items of which the diet is composed. The contribution to total radionuclide intake for each foodstuff, is the product of the quantity of food consumed and radionuclide concentration in that food. Since each different foodstuff may theoretically be a contributor, the investigator is generally faced with a wide variety of foodstuffs too numerous to analyze separately, thus some reasonable selection of the more important foods must be made. The choice of foods for analysis will depend on the basic objective of the survey and the precision desired. The various factors that must be considered in the selection of foods for analysis are discussed below.

A. Quantity of Food Consumed

A choice of foodstuffs or a compilation of a diet representative of the mean intake of a population cannot be made in the absence of adequate food consumption data. Survey results can only be as valid and applicable as the basic food consumption data used, regardless of the precision of the analytical determinations. Information already available on food consumption can often be utilized. The U.S. Department of Agriculture has reported on food consumption patterns within the United States. (1) Detailed information on food consumption for smaller populations or of special groups can be obtained only through appropriately designed surveys. This may be accomplished by means of records of food brought into the home by the housewife. Special surveys would be required if information on individual food consumption was desired.

B. Radionuclide Behavior In Food Chains

In selecting foods for analysis consideration must be given to those foods most likely to contain significant amounts of the radionuclides of interest. The selection of such foods must be based on knowledge of (1) the likelihood of contamination and (2) the passage of radionuclides through the food chain.

1. LIKELIHOOD OF CONTAMINATION

The relative degree of contamination of agricultural products will depend upon the levels of activity in air, water and soil and their interrelations. In periods of relatively high deposition of new activity, surface contamination on the growing plant may be the most important consideration. In other instances, crops irrigated by contaminated water might be the most significant, but in any case the mode of contamination must be considered. Further, with processed food, the decay of specific radionuclides may be an important factor. For example, although milk itself may be a prime contributor of dietary radioiodine, processed milk products such as cheese would be relatively unimportant because of the physical decay of activity during processing.

2. METABOLIC BEHAVIOR IN FOOD CHAINS

The probable metabolic behavior of radionuclides in food chains can be inferred from knowledge of the behavior of the stable elements. The outstanding example of the latter is the similarity in behavior of Ca and Sr in biological systems. This has resulted in selection for analysis for radiostrontium, those foods which are the major dietary source of calcium. In the United States this is in general the basis for the wide spread analysis of milk for Sr^{90}. In eastern countries, such as Japan, dietary calcium is derived mainly from cereals, vegetables and fish. Therefore, these items may be of greater interest than milk in evaluating the radiostrontium intake. It must be realized that although calcium levels in foods are important in deciding which items may be significant contributors of Sr^{90}, the actual contribution will be greatly affected by differential movement of the two nuclides through the food chain and by the proportion of the food in the total diet. Thus, although milk may provide about 80% of the dietary calcium, it provides a smaller proportion of dietary radiostrontium due to the discrimination against Sr^{90} relative to calcium within the cow. It should also be pointed out that if contamination is due to direct deposition on vegetation, the level of Sr^{90} will not have any predictable relation to the calcium content of the vegetation. These reservations must be clearly understood in using dietary sources of calcium as a basis for selecting foods for analysis of radiostrontium.

C. Indicators of Fluctuation

Some foodstuffs which are major contributors of radionuclides may be selected for special study as indicators of changes in the level of radionuclides in the diet. The analysis of milk for radioiodine is a prime example of this type of sampling.

D. Importance To Special Groups

Foods may also be selected when they are of particular importance in the diets of special groups. Very young children for example, may have a diet consisting largely of milk. Thus, milk is an essential item to sample.

IV. SUMMARY

In planning a program for the estimation or evaluation of radionuclide intake, a great number of factors effecting the adequacy and applicability of the sampling data must be considered. In general, the pre-planning, including a definition of the survey objectives, can be as important as the actual analysis to be performed. Adequate planning before a given survey is undertaken may eliminate or minimize much needless effort. It should be remembered that no single survey design can meet all objectives, and that each individual program must be considered in terms of its basic objectives.

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GPO 921-889

Calculation Of Radioactivity Concentration Guides

(Maximum Permissible Concentrations - Water)

I. BASIS FOR ESTIMATING RADIOACTIVITY CONCENTRATION GUIDES (RCG)

A. For Continuous Exposure of Radiation Workers

1. For bone-seeking radionuclides such as Sr^{90}, Pu^{239}, etc. which emit significant amounts of particulate radiation, the estimate is based on a comparison with one tenth microcurie (0.1 μc) of Ra^{226} plus daughter products.(1) This amount of Ra^{226} and its daughters in the body corresponds to an average dose rate to the bone of 28 rems per year (0.56 rem/wk).

2. For all other radionuclides, the Radiation Concentration Guides (RCG) and Permissible Body Burden (PBB) values are set to limit the RBE dose received by radiation workers to:(1)(2)

a. 5 rems per year to gonads and total body (0.1 rem/week)

b. 30 rems per year to skin and thyroid (0.6 rem/week)

c. 15 rems per year to other soft tissue (0.3 rem/week)

B. For Continuous Exposure of the General Population

For individuals in the general population, the Federal Radiation Council has recommended the use of Radiation Protection Guides (RPG) and Radioactivity Concentration Guides (RCG) at a level one tenth those for continuous exposure of radiation workers.

II. DERIVATION OF PERMISSIBLE BODY BURDEN (PBB)

For each radionuclide, there is a specific amount, which if present in the body, would result in a dose rate to the body or one of its organs equal to the applicable RBE dose limit (RPG). This amount or quantity is defined as the Permissible Body Burden (PBB).

For a given radionuclide, it is possible to calculate the dose rate, to the body or one of its organs, that would result from a quantity (q) of that radionuclide in the body. If the resultant dose rate from (q) is specified to be the (RPG), then (q) would be the Permissible Body Burden (PBB).

For the sake of clarity the (PBB) will be calculated in a step-wise manner, determining in turn (A) the concentration in the critical organ, (B) the energy released per gram of tissue, and (C) the energy released in terms of dose. The energy released in terms of dose can then be equated to the Radiation Protection Guide (RPG) and the Permissible Body Burden (q) determined.

A. Concentration in Critical Organ

If the following are defined as indicated:

q = quantity of radionuclide in body in (μc)

f_2 = fraction of (q) in the critical organ

m = mass of critical organ in grams

Then the concentration in the critical organ in terms of μc per gram would be:

$$\frac{qf_2}{m} = \mu c/gm$$

B. Energy Released to Tissue (Per Week)

Using the concentration in the critical organ as shown above, the energy released to the tissue can be calculated.

Let:

3.7×10^4 = disintegrations per second per μc or $\left(\frac{dis}{sec\text{-}\mu c}\right)$

$\Sigma EF(RBE)n$ = Effective absorbed RBE energy per disintegration in $\left(\frac{Mev(RBE)^{*}}{dis}\right)$

6.05×10^5 = Seconds per week or $\left(\frac{sec}{wk}\right)$

The energy released to the tissue per week would then be:

$$\left(\frac{qf_2}{m}\right) \times \left(3.7 \times 10^4\right) \times \left(6.05 \times 10^5\right) \left(\times\, \Sigma EF(RBE)n\right) = \frac{\mu c}{gm} \times \left(\frac{dis}{sec\text{-}\mu c}\right) \times \left(\frac{sec}{wk}\right) \times \frac{Mev(RBE)}{dis} = \frac{Mev(RBE)}{wk\text{-}gm}$$

or

$$\frac{Mev(RBE)}{wk\text{-}gm} = 2.24 \times 10^{10} \left(\frac{qf_2}{m}\right) \Sigma EF(RBE)n$$

C. Energy Released in Terms of Dose Rate

Based on the relative biological effective energy released to the tissue in (RBE) Mev per week per gram, the energy released in terms of dose in rems per week can be calculated:

Let:

1.6×10^{-6} ergs = 1 Mev

1 rad = 100 ergs/gm

rems = rads (RBE)

The energy released to the tissue in rems per week would then be:

$$(2.24 \times 10^{10}) \left(\frac{qf_2}{m}\right) \left(\Sigma EF(RBE)n\right) \times (1.6 \times 10^{-6}) \times \left(\frac{1}{100}\right) = \frac{Mev(RBE)}{wk\text{-}gm} \times \frac{ergs}{Mev} \times \frac{rad}{erg/gm} = rad(RBE)/week = rem/week$$

or

$$rems/week = 3.58 \times 10^{2} \left(\frac{qf_2}{m}\right) \Sigma EF(RBE)n$$

If the dose in rems per week is equated to the RPG denoted as W, then:

$$W = 3.58 \times 10^{2} \left(\frac{qf_2}{m}\right) \Sigma EF(RBE)n$$

and

$$q = \frac{2.8 \times 10^{-3} mW}{f_2\ \Sigma EF(RBE)n}$$

D. Example

The following example, considering Cs^{137} + Ba^{137m} as the radionuclide contaminant, illustrates the use of the above relationship to determine the (PBB). For this example, the total body is assumed to be the critical organ.

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*The method of evaluating ΣEF(RBE)n is quite involved and will not be discussed in this lecture outline. For further information see reference(4). The term as used here has been defined so as to give the effective RBE energy per disintegration. That is, using this term, the dose rate as calculated in Part C is given directly in Rem units.

Given:

Radionuclide Contaminant = $Cs^{137} + Ba^{137m}$

$W = 0.1$ rem/wk

$m = 70{,}000$ grams (total body)

$f_2 = 1$ (since total body is critical organ)

$\Sigma EF(RBE)n = 0.59$ Mev(RBE) (from Reference 4)

$$\therefore\ q = \frac{2.8 \times 10^{-3}\,(70{,}000)\,(0.1)}{(1)\,(0.59)}$$

$$q = 33\ \mu c$$

This compares to the value (30 μc) given in Handbook 69.[(1)]

III. DERIVATION OF (RCG) IN WATER FOR RADIATION WORKERS

A. General Expression for RCG

A general expression for the Radioactivity Concentration Guide (RCG) in water for continuous ingestion by radiation workers (168 hour week) can be derived quite readily by considering the rate of accumulation of a radionuclide in the critical organ. This rate of accumulation can be expressed as follows:

(Rate of Accumulation) = (Rate of Uptake) − (Rate of Loss)

For simplicity the two terms on the right of the equality will be taken separately.

1. RATE OF UPTAKE

The rate of uptake can be expressed on the basis of the volume of liquid consumed, the concentration of radionuclide in the liquid, (that is, the rate of intake) and the fraction of the ingested radionuclide that is deposited in the critical organ:

or

Uptake = (Intake) (Fraction Deposited)

Uptake = (Volume) (Concentration) (Fraction Deposited)

or

$$\text{Uptake} = 2200\,(RCG)_w\,f_w$$

where:

2200 = milliliters of liquid consumed per day by Standard Man.

$(RCG)_w$ = Radioactivity Concentration Guide for water in μc/cc

f_w = Fraction of ingested radionuclide that is deposited in critical organ.*

2. RATE OF LOSS

The rate of loss of radionuclide from the critical organ can be expressed as a combination of the loss from biological elimination and the loss by radioactive decay, expressed mathematically as follows:

$$\text{Loss} = (qf_2)\,(\lambda_b + \lambda_r) = (qf_2)\,\lambda_e$$

where: (qf_2) = quantity of radionuclide in the critical body organ in microcuries.

λ_b = Biological elimination constant**

λ_r = Radioactive decay constant

λ_e = Effective decay constant or $(\lambda_b + \lambda_r)$

The above equation for the loss of radionuclide can be made somewhat easier to

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*The value of f_w will depend on the particular organ being considered as critical.

**Based on the assumption that the biological elimination of radionuclide from the critical organ follows the simple exponential law:[(4)]

$$\left(\frac{d\,(qf_2)}{dt}\right)_b = -\lambda_b\,(qf_2)$$

handle by introducing an effective half-life (T_e) in place of the effective decay instant (λ_e). The effective half-life is defined in the same manner as radioactive half-life:

$$\lambda_e = \frac{0.693^*}{T_e}$$

and the equation for loss becomes:

$$\text{Loss} = (qf_2)\,\frac{0.693}{T_e}$$

B. Rate of Accumulation

The rate of accumulation may now be rewritten from the original expression by combining the rates of uptake and loss as derived above:

(Rate of Accumulation)

$$= 2200\,(RCG)_w f_w - (qf_2)\,\frac{0.693}{T_e}$$

Since the rate of accumulation is simply the rate of change of the quantity of radionuclide in the critical organ with respect to time, the above equation can be rewritten in differential form as:

$$\frac{d(qf_2)}{dt} = 2200\,(RCG)_w f_w - (qf_2)\frac{0.693}{T_e}$$

C. Calculation of RCG Assuming Body Equilibrium

A vast majority of radionuclides, because of their relatively short effective half-lives (T_e), can be said to reach body equilibrium for conditions of continuous intake within a matter of a few years. In considering such radionuclides the computation of the (RCG) values may be greatly simplified by assuming equilibrium conditions have been reached. If body equilibrium in relation to radionuclide intake is defined as that condition which exists when radionuclide uptake is exactly equal to radionuclide loss, then:

$$\frac{d\,(qf_2)}{dt} = 0 \text{ and Uptake } = \text{ Loss}$$

Expressing uptake and loss in terms of the relationships already derived:

$$2200\,(RCG)_w f_w = (qf_2)\,\frac{0.693}{T_e}$$

and:

$$(RCG)_w = \frac{(qf_2)\,0.693}{2200\,f_w T_e}$$

Since at equilibrium the amount of radionuclide in the critical organ (qf_2) does not change, and since the $(RCG)_w$ should be such that the Permissible Body Burden is not exceeded, (qf_2) in the above equation is taken to be the permissible burden for the critical organ.

1. EXAMPLE

Consider the example already given, Cs^{137} + Ba^{137m} (total body assumed as critical organ).

Given:

qf_2 = (33 μc) (1) = 33 μc.

f_w = 1.0 (since essentially all ingested radionuclide is absorbed by blood)

T_e = 70 days

$$RCG_w = \frac{(33)\qquad(0.693)}{(2200)\,(1.0)\,(70)} = 1.5 \times 10^{-4}\,\mu c/ml$$

which is comparable to $2 \times 10^{-4}\,\mu c/ml$ given in Handbook 69 for continuous occupational exposure.

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*From consideration of the relationships $\lambda_b = \frac{0.693}{T_b}$ and $\lambda_r = \frac{0.693}{T_r}$ one would find

$$T_e = \frac{T_r T_b}{T_r + T_b}$$

D. Calculation of $(RCG)_w$ for the General Non-equilibrium Case

A number of radionuclides do not reach equilibrium in the body even after periods of continuous intake as long as fifty years (the basis for RCGs). These are listed in Table I. For cases involving such radionuclides, the differential expression for the rate of accumulation as given in Part B above can be integrated and solved to give the following general solution:

$$(RCG)_w = \frac{0.693\,(qf_2)}{(2200)\,T_e f_w \left(1 - e^{-\frac{0.693(t)}{T_e}}\right)}$$

Since the $(RCG)_w$ is based on continuous intake for a period of fifty years, (t) can be replaced in the above equation by (365 days/yr) (50 yrs.) or 1.82×10^4 days, and rewritten as:

$$(RCG)_w = \frac{0.693\,(qf_2)}{2200\,T_e f_w \left(1 - e^{\frac{-1.26 \times 10^4}{T_e}}\right)}$$

Since the $(RCG)_w$ should be such that the Permissible Body Burden is not exceeded during this period, (qf_2) in the above equation is taken to be the permissible burden in the critical organ.

1. EXAMPLE:

Strontium-90 is one of the more important radionuclides that does not reach equilibrium in the body within a fifty year period. The following example illustrates the use of the general solution for $(RCG)_w$ using Sr^{90} as an example.

Given Sr^{90} (assume bone to be critical organ)

$(qf_2) = (2.0\ \mu c)\ (0.99) = 2.0\ \mu c$

$f_w = 0.09$

$T_e = 6.4 \times 10^3$ days

$(RCG)_w$

$$= \frac{0.693\ (2.0)}{(2200)(6.4 \times 10^3)(0.09)\left(1 - e^{-\frac{1.26 \times 10^4}{6.4 \times 10^3}}\right)}$$

$$= \frac{1.386}{(12.7 \times 10^5)\ (0.86)} = 1.3 \times 10^{-6}\ \mu c/ml$$

which is comparable to the value of 1×10^{-6} $\mu c/ml$ given in Handbook 69.(1)

IV. TABULATED SUMMARY OF DATA

In Table II, the RCG and PBB for continuous occupational exposure (168 hour week) and the information necessary for calculating both have been tabulated for various radionuclides. The recommended RCG's(1) for individuals in the general population are also listed, being one tenth the values for continuous occupational exposure, as previously discussed.

Table 1

RADIONUCLIDES WHICH DO NOT REACH EQUILIBRIUM IN THE BODY WITHIN 50 YEARS

Radionuclide	Radioactive half-life T_r (yr)	Biological half-life T_b (yr)	Effective half-life T_e (yr)	Percent equilibrium reached in 50 yr
Sr^{90}	28	50	18	86
Ra^{226}	1622	45	44	56
Ac^{227}	21. 8	200	20	83
Th^{230}	8.0×10^4	200	200	16
Th^{232}	1.39×10^{10}	200	200	16
Pa^{231}	3.4×10^4	200	200	16
Np^{237}	2.20×10^6	200	200	16
Pu^{238}	89. 6	200	62	43
Pu^{239}	2.44×10^4	200	200	16
Pu^{240}	6.6×10^3	200	190	16
Pu^{241}	13. 2	200	12	94
Pu^{242}	3.8×10^5	200	200	16
Am^{241}	462	200	140	22
Am^{243}	8×10^3	200	200	16
Cm^{243}	35	200	30	69
Cm^{244}	18. 4	200	17	87
Cm^{245}	2×10^4	200	200	16
Cm^{246}	6.6×10^3	200	190	16
Cf^{249}	4.7×10^2	200	140	22
Cf^{250}	10	200	10	97

Table 2

BACKGROUND DATA FOR CALCULATING RADIOACTIVITY CONCENTRATION GUIDES IN DRINKING WATER

Organ		Radiation Protection Guide (For Occupational Exposure)		Radionuclide Characteristics					Body Burden and Concentration Guides		
Name	Mass (gms)	Per Year (rems)	Per Week (rems)	Symbol	f_2	$\Sigma EF(RBE)n$ $\left(\frac{Mev(RBE)}{dis}\right)$	f_w	T_e (days)	PBB (μc)	$(RCG)_w$ for Continuous Ingestion (μc/ml)	
										Radiation Workers	Individuals in General Population
Total Body	70,000	5	0. 1	Cs^{137} + Ba^{137m}	1. 0	0. 59	1. 0	70	30	2×10^{-4}	2×10^{-5}
Single Organ											
General		15	0. 3								
Thyroid	20	30	0. 6	I^{131} + Xe^{131m}	0. 2	0. 23	0. 3	7. 6	0. 7	2×10^{-5}	2×10^{-6}
Bone	7,000	28	0. 56	Sr^{90} + Y^{90}	0.99	5. 5	0.09	6,400	2. 0	1×10^{-6}	1×10^{-7}

f_2 = Fraction in Critical Organ

T_e = Effective Half-Life in days

f_w = Fraction uptake by ingestion

$\Sigma EF(RBE)n$ = Effective energy per disintegration

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This lecture outline is based on a report originally prepared for Radiological Health Training Activities by Mr. Myron F. Fair, Assistant Chief, Education and Training Section, Health Physics Division, Oak Ridge National Laboratory.

GPO 878-270

Internal Dose Calculations

I. INTRODUCTION

The deposition of radionuclides within the human body may result in damage to body organs. Since much work has been done in establishing a dose-effect relationship for irradiation of biological systems, one of the prime considerations in evaluating the potential hazard from internal emitters is the biological dose received by various organs. Presented here is an outline of the methods used in calculating these doses.

II. BACKGROUND INFORMATION

A. Critical Body Organ

The critical body organ as defined by the International Commission on Radiological Protection is "that organ of the body whose damage by the radiation results in the greatest damage to the body." It follows that in most cases one will be interested in calculating the dose to the critical organ for the particular radionuclide in question. This will usually be the organ in which the radionuclide concentrates most. One of the best known examples is ^{131}I which has for its critical organ the thyroid gland. Many radionuclides have more than one critical organ.

B. Assumptions

1. PHYSICAL

All alpha, beta, and recoil energies are assumed to be absorbed by the organ. Corrections are made for gamma components.(1)

2. BIOLOGICAL

a. Except in the case of bone, the radionuclide is assumed to be uniformly distributed in the organ.

b. All biological constants are taken from "standard man" data. It should be remembered that these values may vary considerably among individuals.

c. Biological elimination is assumed to follow an exponential relationship.[1]

C. Continuous vs. "One-shot" Intake

The calculations herein deal with two types of situations, continuous intake and a "one-shot" intake. Continuous intake means the radionuclide is being continually taken into the body at a constant rate. An example of continuous intake is the ingestion over a long period of time of milk or water which contains ^{90}Sr or other fission products. A "one-shot" intake refers to the ingestion or inhalation of a quantity of some radionuclide over a relatively short period of time. The administration of a single diagnostic or therapeutic dose of ^{131}I would fall into this category.

D. Units

The following units will be utilized in the derivations:

q = amount of radionuclide in total body (μCi)

f_2 = fraction of q that reaches organ

qf_2 = amount of radionuclide in organ (μCi)

m = mass of organ (gm)

P = rate of uptake by organ (μCi per unit time)

$P = \frac{\text{volume}}{\text{time}} \times \text{concentration} \times f_w$, where f_w equals the fraction of the radionuclide ingested which reaches the organ. In the case of airborne activity this factor is f_a, which is the fraction of that inhaled which reaches the organ. For simplicity in this outline, f_w will be used throughout.

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[1] This is a good assumption for most radionuclides. Some, however, seem to follow a power function in both uptake and biological elimination.

III. DERIVATION OF FORMULAS

Since the dose received by the organ is directly proportional to the amount of the radionuclide in the organ, the first task is to calculate qf_2. From this the dose rate at any time and finally the total dose to the organ over any specified period of time can be calculated.

A. Expression for Calculating Amount of Radionuclide in Organ

1. CONTINUOUS INTAKE

It is assumed that the radionuclide builds up exponentially in the organ as indicated in Figure 1. This is illustrated in Figure 2 by a one compartment bucket analogy where P is the rate of uptake by the organ and $\lambda_{eff}(qf_2)$ is the rate of loss.[2]

This relationship can be stated in the form of the differential equation:

$$\frac{d(qf_2)}{dt} = P - \lambda_{eff}(qf_2) \qquad (1)$$

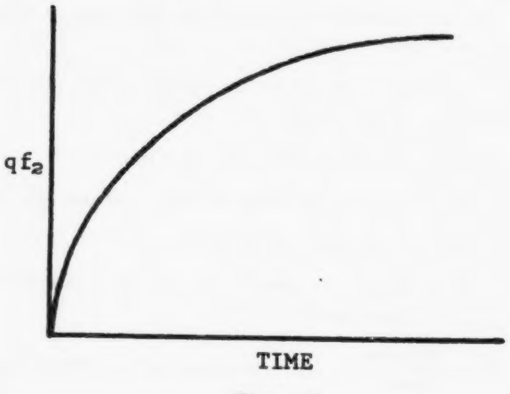

Figure 1

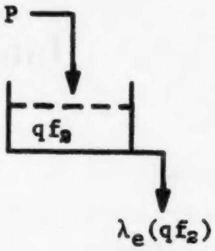

Figure 2

where $\frac{d(qf_2)}{dt}$ is the time rate of change of the amount of radionuclide in the organ. Integrating Eq. (1) yields:

$$qf_2 = \frac{P}{\lambda_{eff}}(1 - e^{-\lambda_{eff}t}) \qquad (2)$$

This expression can be used to find the amount of the radionuclide in the organ at any time after intake has begun. It is observed that for materials with a short effective half life, the factor, $(1 - e^{-\lambda_{eff}t})$ quickly approaches one, which simplifies the equation. In this case it is said that the material reaches equilibrium in the organ.

2. "ONE-SHOT" INTAKE

In this case the amount of the radionuclide in the organ decreases exponentially as indicated in Figure 3.[3]

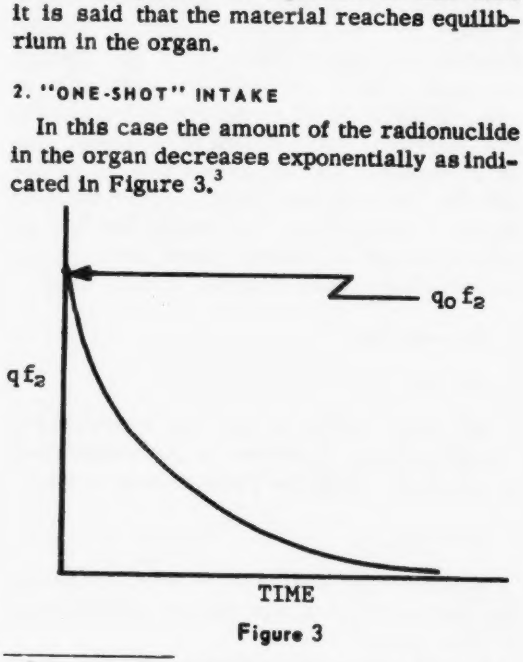

Figure 3

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[2] λ_{eff} is the effective decay constant

$\lambda_{eff} = \lambda_r$ (radiological constant) + λ_b (biological constant)

$\lambda_{eff} = \frac{.693}{T_{eff}}$ where T_{eff} is the effective half life

[3] Here the time of buildup in the organ is neglected. This time is usually small compared to the time over which the dose is protracted.(2)

It is usually advantageous to relate qf_2 to the intake which is the known quantity. Since this is an exponential relationship, it can be written as follows:

$$qf_2 = q_0 f_2 e^{-\lambda_{eff} t} \tag{3}$$

By definition, $q_0 f_2 = A_0 f_w$, where A_0 is the amount of the radionuclide ingested. Substituting into Eq. (3).

$$qf_2 = A_0 f_w e^{-\lambda_{eff} t} \tag{4}$$

B. To Calculate Dose Rate to Organ

As stated previously, the dose rate to an organ is proportional to the amount of the radionuclide in the organ. Thus having determined qf_2 previously, the dose rate can be found. The unit of time here is arbitrary. Since RPG's can be broken down on a weekly basis, the expression for the dose rate will be derived in terms of rems per week.

$$D_r = \frac{qf_2}{m} \left| \; 3.7 \times 10^4 \; \right| \; 6.05 \times 10^5 \; \left| \; \frac{{}^4\Sigma EF\ (RBE)n}{} \; \right| \; 1.6 \times 10^{-6} \; \left| \; \frac{1}{100} \; \right|$$

$$\frac{\mu Ci}{gm} \cdot \frac{dis}{sec\text{-}\mu Ci} \cdot \frac{sec}{wk} \cdot \frac{MeV(RBE)}{dis} \cdot \frac{ergs}{MeV} \cdot \frac{rad}{ergs/gm}$$

$$\longrightarrow \frac{rem}{wk}$$

$$D_r = 3.58 \times 10^2 \frac{(qf_2)}{m} \Sigma EF\ (RBE)n \tag{5}$$

1. CONTINUOUS INTAKE

The dose rate (D_r in rem/wk) at any time (t) after continuous intake has begun is found by substituting the value of qf_2 from Eq. (2) into Eq. (5) which yields:

$$D_r = 3.58 \times 10^2 \left(\frac{P}{m\lambda_{eff}}\right) \Sigma EF(RBE)n \times (1 - e^{-\lambda_{eff} t}) \tag{6}$$

2. "ONE-SHOT" INTAKE

Here the value of qf_2 from Eq. (4) is substituted into Eq. (5) obtaining:

$$D_r = 3.58 \times 10^2 \left(\frac{A_0 f_w}{m}\right) \Sigma EF(RBE)n \times e^{-\lambda_{eff} t} \tag{7}$$

where D_r is the dose rate at any time (t) after the material is deposited in the organ.

C. To Calculate Total Dose (5)

The total dose from any time (t_1) to time (t_2) after intake is equal to the integral of the dose rate over that period of time. Or

$$D_{t_1}^{t_2} = \int_{t_1}^{t_2} D_r dt.$$

1. CONTINUOUS INTAKE

The dose rate to the organ will build up according to the curve in Figure 4.

---

[4] The method of evaluating $\Sigma EF(RBE)n$ is quite involved and will not be discussed here. In this term, E is the total energy (MeV) absorbed in the organ per disintegration of the radionuclide, RBE is the relative biological effectiveness of the radiation, n is a relative damage factor used to compensate for nonuniformity of distribution of radionuclides deposited in the bone, F is the ratio at time t of the number of disintegrations per unit time of daughter atoms to the number of disintegrations per unit time of parent atoms in the critical organ.(3, 4)

The term as used here has been defined so as to give the effective RBE energy per disintegration. That is, using this term, the dose rate is given directly in rem units.

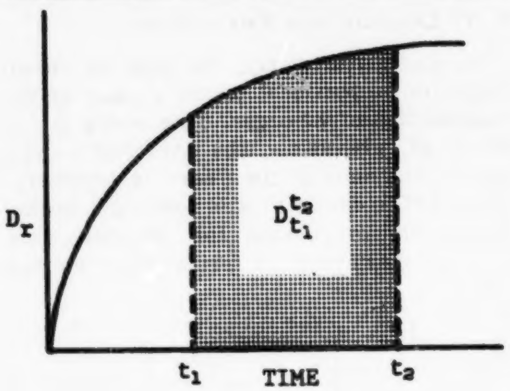

Figure 4

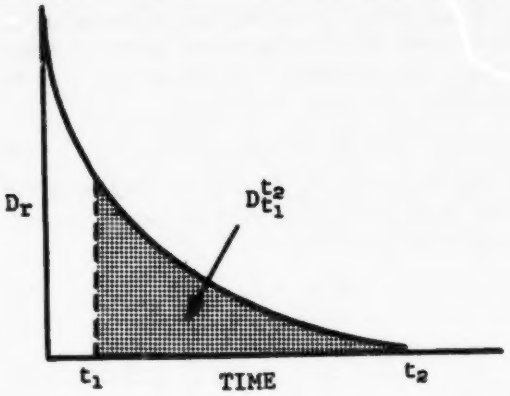

Figure 5

By integrating Eq. (6) over the time interval t_1 to t_2 the total dose during this period is obtained. This dose ($D_{t_1}^{t_2}$) is represented by the shaded area in Figure 4. The integration yields:

$$D_{t_1}^{t_2} = 51.1 \left(\frac{P}{m\lambda_{eff}}\right) \Sigma EF(RBE)n \times \left[t_2 - t_1 - \frac{1}{\lambda_{eff}}\left(e^{-\lambda_{eff}t_1} - e^{-\lambda_{eff}t_2}\right)\right]^*$$

A simplified and more practical form of this equation can be obtained by substituting zero for t_1. This gives:

$$D_o^t = 51.1 \left(\frac{P}{m\lambda_{eff}}\right) \Sigma EF(RBE)n \times \left[t - \frac{1}{\lambda_{eff}}\left(1 - e^{-\lambda_{eff}t}\right)\right]^* \quad (8)$$

2. "ONE-SHOT" INTAKE

This type of situation gives a dose rate versus time curve as shown in Figure 5. The dose from t_1 to t_2 is obtained by integrating Eq. (7). This gives:

$$D_{t_1}^{t_2} = 51.1 \left(\frac{A_o f_w}{\lambda_{eff} m}\right) \Sigma EF(RBE)n \left(e^{-\lambda_{eff}t_1} - e^{-\lambda_{eff}t_2}\right)$$

Setting t_1 equal to zero, as was done previously, yields:

$$D_o^t = 51.1 \left(\frac{A_o f_w}{\lambda_{eff} m}\right) \Sigma EF(RBE)n \times \left(1 - e^{-\lambda_{eff}t}\right) \quad (9)$$

Many times one is interested in the total infinite dose received from a "one-shot" intake. This can be obtained merely by substituting for t in Eq. (9). The following equation results:

$$D_o^{\infty} = 51.1 \left(\frac{A_o f_w}{\lambda_{eff} m}\right) \Sigma EF(RBE)n \quad (10)$$

which gives the total infinite dose.

D. Special Applications

The preceding relationships can be made to apply to a variety of situations. For example, suppose a person ingests a radionuclide continuously for some period of time, and then ingestion stops. The problem is to find the total dose delivered to a particular organ from the ingestion.

The situation is represented graphically in Figure 6.

By rearranging equations (8) and (10) and combining them, one can easily come up with the following expression for the total dose.

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* The constant 51.1 was obtained by dividing 358 by 7 to get D_r in terms of rem/day since T_{eff} is usually given in days.

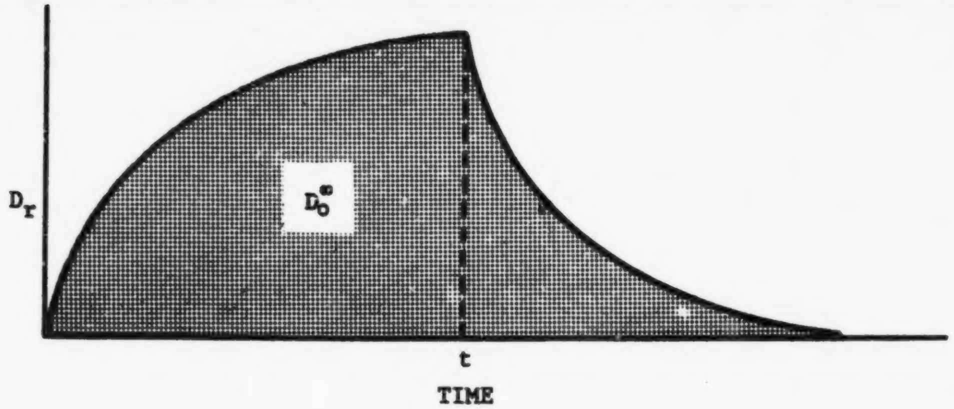

Figure 6

$$D_o^\infty = 51.1 \left(\frac{P}{m\lambda_{eff}}\right) \Sigma EF(RBE)n(t), \text{ where}$$

t is the time at which ingestion stopped.

Other complex problems can be solved by manipulating these basic relationships.

IV. SUMMARY

The preceding equations will enable one to calculate the approximate biological dose to body organs resulting from radionuclides being deposited in the body. To say that the results will be one hundred percent accurate in all cases would be a gross misrepresentation. As more knowledge is gained about the behavior of certain radionuclides in the body, biological and physical constants will change. Also, some error may be introduced as a result of the assumptions stated previously. Hopefully, these will be of small magnitude. The relationships are, however, extremely useful in helping to establish guidelines by which to govern radiation exposure. It is strongly suggested that the reader study reference 1 in order to understand more thoroughly the significance of calculations such as these.

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This material was prepared by Mr. G. H. Simmons of the Cincinnati Radiological Health Training Section, Training Branch, DRH.

Dose from Radionuclide Combinations

I. INTRODUCTION

A. The presence of radiocontaminants in the environment may range from one radionuclide in one environmental phase to multiple contaminants in multiple environmental phases.

B. Evaluation of the overall health significance of such contaminants requires an understanding of the concept of Radioactivity Concentration Guides or "Maximum Permissible Concentrations",* and the additive effects of multiple radiation sources.

II. RADIOACTIVITY CONCENTRATION GUIDES

The inhalation or ingestion of radioactive materials leads to radiation exposure of the body. Control of the dose rate from such exposure depends upon limiting the concentrations of radiocontaminants in the several environmental phases (i.e., air, water, milk and food). As an approach to a discussion of the meaning of Radioactivity Concentration Guide (RCG), a single radioactive material in one environmental phase, namely water, will be considered. The problem will be discussed initially on the basis of Radiation Protection Guides for radiation workers.

A. Radiation Workers

Ingested radionuclides may deposit somewhat uniformly throughout the body or tend to localize in one or more selected body organs. Each such contaminant must be evaluated in terms of the permissible dose rate for the portion or portions of the body affected.

1. WHOLE BODY EXPOSURE

a. The element cesium is distributed rather uniformly throughout the body. Experimental and theoretical studies have shown that the presence in the body (of "standard" man) of 30 microcuries of one radioactive isotope of cesium, namely, Cs^{137}, will yield a whole body dose rate of 5 rems per year. This corresponds to the Radiation Protection Guide (exclusive of exposures from background and purposeful application in the healing arts) for radiation workers.(1)(12) The quantity, 30 microcuries, is referred to as the Permissible Total Body Burden for Cs^{137} in radiation workers.(3)

b. If, however, 30 microcuries of Cs^{137} were deposited within the body, it would not remain there long because of biological elimination and radioactive decay. Therefore, a certain amount could be continually ingested without the Body Burden being exceeded.

c. Standard man consumes approximately 2200 milliliters of water per day. About one half of this is ingested during the working hours.(3) If the daily intake of Cs^{137} via drinking water is to be limited such that the Total Permissible Body Burden will not be exceeded (and the average yearly radiation worker whole body dose rate not exceed 5 rems), then the concentration of Cs^{137} in the drinking water must not exceed 4×10^{-4} $\mu c/ml$, is the Radioactivity Concentration Guide (RCG) or Maximum Permissible Concentration for Cs^{137} in drinking water for consumption by radiation workers based on an 8-hour day, 40-hour work week.(3)

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* The term "Radioactivity Concentration Guide" has been recently suggested by the Federal Radiation Council since the term Maximum Permissible Concentration as used by the NCRP and ICRP is often interpreted as an upper limit never to be exceeded rather than a maximum average.

d. If this same water supply were the only one available to a radiation worker - that is, if he were to consume it continuously (168 hours per week) - the Radioactivity Concentration Guide would have to be lowered to 2×10^{-4} $\mu c/ml$.(3)

2. SINGLE ORGAN EXPOSURE

a. The element iodine is well known for its characteristic localization in the thyroid. The Permissible Body Burden for I^{131} is 0.7 microcurie. This amount, deposited in the body, will result in the thyroid receiving an average dose rate of 30 rems per year (the permissible average for that organ for radiation workers).*(3)

b. The quantity of I^{131} deposited in the body is gradually reduced through biological elimination and radioactive decay. Theoretical and experimental data show that if drinking water is the sole body source of I^{131}, its concentration must be restricted to 6×10^{-5} $\mu c/ml$ if the Permissible Body Burden is not to be exceeded.

This value, 6×10^{-5} $\mu c/ml$, is the RCG for I^{131} in drinking water to be consumed by radiation workers, based upon the thyroid as the critical body organ, and assuming consumption of such water only during an 8-hour day, 40-hour week.(3)

c. If this same water supply were the only source available to a radiation-worker, the RCG for I^{131} would have to be lowered to 2×10^{-5} $\mu c/ml$.(3)

B. Population Groups

Radiation Protection Guides (and Radioactivity Concentration Guides) for the general population are considerably below those for radiation workers for a number of reasons. For example, the general population contains children and infants which are particularly sensitive to radiation damage, the population contains a large part of the germ plasm controlling the future of the race; and the number of years of exposure to radiation in the course of employment will be less than the average total life span.

1. INDIVIDUALS IN THE GENERAL POPULATION

a. Currently it is recommended that the yearly radiation exposure of individuals in general population (exclusive of natural background and deliberate exposure of patients by practitioners of the healing arts) should be held to one-tenth of the levels permitted for continuous occupational exposure (i.e. on the basis of 168 hours per week.)(3)

b. Thus the recommended permissible average whole body dose rate for such groups (exclusive of exposures from background and medical and dental x-ray procedures) is 0.5 rem per year.

c. Following these recommendations, the RCG for Cs^{137} in drinking water for persons living near atomic energy plants would be 2×10^{-5} $\mu c/ml$. Similarly, the RCG for I^{131} would be 2×10^{-6} $\mu c/ml$.

2. AVERAGE POPULATION GROUPS

a. If the radiation exposure of individuals in the general population is not permitted to exceed the Radiation Protection Guides outlined above, the average exposure of the total population (this includes radiation workers, special groups and the general population) will be less than the permissible for individuals in the general populations: 1) The Federal Radiation Council suggests the use of the arbitrary assumption that the majority of individuals do not vary from the average by a factor greater than three. 2) Thus, they recommend the use of 0.17 rem as a Radiation Protection Guide for yearly whole-body exposure of average total population groups. 3) This is in keeping with their recommendation that the average genetically significant dose to the total population not exceed 5 rems up to age 30 (exclusive of natural background and purposeful exposure of patients by practitioners of the healing arts).

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* For the bone or skin, a similar permissible average dose rate would apply. For radionuclides exposing the gonads, RCG values must be such as to limit the dose rate to that organ to 5 rems per year. RCG values for radionuclides concentrating in other organs are calculated so as to limit the dose rate to 15 rems per year.(3)

b. Following these assumptions it would be anticipated that if no individual in the general population consumed drinking water containing more than the recommended Radioactivity Concentration Guide (for example 2×10^{-5} μc/ml for Cs^{137}) then the average concentration being consumed by the total population would be approximately one third this value (for example 7×10^{-6} μc/ml for Cs^{137}).

III. MULTIPLE RADIOCONTAMINANTS

A. One Environmental Phase - Individuals in the General Population

As the variety of nuclear applications increases, situations will often be encountered in which several radionuclides will be present in the drinking water to be consumed by man. To assure that combinations of such nuclides do not result in permissible dose rates being exceeded, additional knowledge of the concepts underlying Radioactivity Concentration Guides is needed. Procedures for the evaluation of the health significance of values will be in accordance with current recommendations of the Federal Radiation Council and the National Committee on Radiation Protection and Measurements for individuals in the general population.(4) (12)

1. WHOLE BODY EXPOSURE

Consider, for example, a drinking water source containing two radiocontaminants, Cs^{137} and H^3. Both cesium and tritium, if ingested, are somewhat uniformly distributed throughout the body.

a. The dose rate to the whole body due to the presence of Cs^{137} and H^3 in drinking water would be:

$(W_1 + W_2)$ (Radiation Protection Guide Whole Body Dose Rate)

where

W_1 = fraction of the RCG for Cs^{137} in drinking water;

W_2 = fraction of the RCG for H^3 in drinking water.

b. If the permissible average whole body dose rate is not to be exceeded, the sum of the fractions, $(W_1 + W_2)$, must not exceed unity.

c. As previously stated, the RCG for Cs^{137} in drinking water for individuals in the general population is 2×10^{-5} μc/ml. For H^3, the RCG is 5×10^{-3} μc/ml. If the drinking water being consumed by the general population contained an average of 1×10^{-5} μc/ml of Cs^{137} and 2×10^{-3} μc/ml, of H^3, the fraction of the permissible average whole body dose rate received from drinking water alone would be:

$$\left[\left(\frac{1 \times 10^{-5}\ \mu c/ml}{2 \times 10^{-5}\ \mu c/ml}\right) + \left(\frac{2 \times 10^{-3}\ \mu c/ml}{5 \times 10^{-3}\ \mu c/ml}\right)\right]$$

d. The whole body dose rate due to consumption of such water, assuming a permissible dose for individuals in the general population from internal sources of 0.5 rem per year, would be:

$$(0.9)\ (0.5\ \text{rem/yr})$$

$$\cong \underline{0.45\ \text{rem/yr}}$$

2. SINGLE ORGAN EXPOSURE

a. Contaminants Affecting the Same Body Organ

1) Consider a drinking water source containing Sr^{90} and Pu^{239}. The critical body organ for both these radionuclides is the bone and the RCG values for individuals in the general population are, respectively, $1 \times 10^{-7}\ \mu c/ml$ and $5 \times 10^{-6}\ \mu c/ml$.

2) If the drinking water under consideration contained an average of $2 \times 10^{-8}\ \mu c/ml$ of Sr^{90} and $7 \times 10^{-7}\ \mu c/ml$ of Pu^{239}, the fraction of the permissible dose rate to bone due to continued ingestion of such water would be:

$$\left[\left(\frac{2 \times 10^{-8}\ \mu c/ml}{1 \times 10^{-7}\ \mu c/ml}\right) + \left(\frac{7 \times 10^{-7}\ \mu c/ml}{5 \times 10^{-6}\ \mu c/ml}\right)\right]$$

$$\cong (0.20 + 0.14) = \underline{0.34}$$

3) The actual resulting bone dose rate would be approximately:

$$(0.34)\ (3.0\ \text{rems/yr}) \cong 1.0\ \text{rem/yr}$$

b. Contaminants Affecting Different Body Organs

1) Assume the water to be consumed by the general population contains I^{131} and Ca^{45}, and that their concentrations are $3 \times 10^{-7}\ \mu c/ml$ and $2 \times 10^{-6}\ \mu c/ml$, respectively.

2) The RCG values for these radionuclides in drinking water are as follows:

$\underline{I^{131}}$

$2 \times 10^{-6}\ \mu c/ml$, assuming the thyroid as the critical body organ

$2 \times 10^{-4}\ \mu c/ml$, assuming the total body to be critical*

$\underline{Ca^{45}}$

$9 \times 10^{-6}\ \mu c/ml$, assuming bone as the critical organ

$7 \times 10^{-5}\ \mu c/ml$, assuming the total body to be critical*

3) Under these circumstances, the dose rate to the thyroid would be approximately:

$$\left[\frac{3 \times 10^{-7}\ \mu c/ml}{2 \times 10^{-6}\ \mu c/ml}\right] \left[3.0\ \text{rems/yr}\right]$$

$$+ \left[\frac{2 \times 10^{-6}\ \mu c/ml}{7 \times 10^{-5}\ \mu c/ml}\right] \left[0.5\ \text{rem/yr}\right]$$

$$\cong (0.15)\ (3.0\ \text{rem/yr})$$

$$+ \ (0.029)\ (0.50\ \text{rem/yr})$$

$$\cong (0.45 + 0.015)\ \text{rem/yr}$$

$$\cong \underline{0.46\ \text{rem/yr}}$$

4) Similarly, the dose rate to the bone would be about:

$$\left[\frac{2 \times 10^{-6}\ \mu c/ml}{9 \times 10^{-6}\ \mu c/ml}\right] \left[3.0\ \text{rems/yr}\right]$$

$$+ \left[\frac{3 \times 10^{-7}\ \mu c/ml}{2 \times 10^{-4}\ \mu c/ml}\right] \left[0.5\ \text{rem/yr}\right]$$

$$\cong (0.22)\ (3.0\ \text{rems/yr})$$

$$+ \ (0.0015)\ (0.5\ \text{rem/yr})$$

$$\cong \underline{0.7\ \text{rem/yr}}$$

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* Although I^{131} localizes principally in the thyroid and Ca^{45} in the bone, the whole body receives a small radiation dose.

d. Mathematically, a drinking water supply could contain concentrations of both I^{131} and Ca^{45} at the listed single organ RCG values without the thyroid or the bone receiving significantly more than the Radiation Protection Guide dose rate. However, several other factors should be considered in the evaluation of the overall effects of radionuclide combinations:

1) Even though every radionuclide in a given radiation source may be known to localize principally in a different body organ, the total effect of the presence of a sufficient number of such contaminants, each at its RCG for the selected critical organ, would ultimately represent a whole body dose rate ranging from 1.5 to 3.0 rems per year.

2) Experimental evidence indicates that certain radionuclide combinations may have synergistic effects.

B. Several Environmental Phases - Individuals in the General Population

Where population groups receive external as well as internal exposure, resulting from the presence of multiple radionuclides in multiple phases of the environment, evaluation of the health significance becomes much more complex. The following example illustrates the general approach.

1. Assume an environment with multiple radiation sources as outlined in Table I.

Table I

Assumed Radiation Source		Assumed Concentration or Level	Radioactivity Concentration Guide or Radiation Protection Guide for Selected Critical Organs	
Cs^{137}	Air	1×10^{-11} μc/ml	2×10^{-9} μc/ml	Total Body
	Water	4×10^{-7} μc/ml	2×10^{-5} μc/ml	Total Body
I^{131}	Air	1×10^{-11} μc/ml	3×10^{-10} μc/ml	Thyroid
			3×10^{-8} μc/ml	Total Body
	Water	9×10^{-8} μc/ml	2×10^{-6} μc/ml	Thyroid
			2×10^{-4} μc/ml	Total Body
Fallout	External	0.005 rem/yr	0.5 rem/yr	Total Body

2. Under these conditions, the Whole Body Dose Rate would be approximately:

$$(A_1 + W_1 + A_2 + W_2 + E_1)\ (0.5\ \text{rem/yr})$$

Where, assuming the total body as the critical organ,

A_1 = fraction of the RCG for Cs^{137} in air

W_1 = fraction of the RCG for Cs^{137} in drinking water

A_2 = fraction of the RCG for I^{131} in air

W_2 = fraction of the RCG for I^{131} in drinking water, and

E_1 = fraction of the Radiation Protection Guide (RPG) for exposure from external sources.

Substituting, the whole body dose rate equals:

$$\left\langle \left[\frac{1 \times 10^{-11}\ \mu c/ml}{2 \times 10^{-9}\ \mu c/ml}\right] + \left[\frac{4 \times 10^{-7}\ \mu c/ml}{2 \times 10^{-5}\ \mu c/ml}\right] + \left[\frac{1 \times 10^{-11}\ \mu c/ml}{3 \times 10^{-8}\ \mu c/ml}\right] + \left[\frac{9 \times 10^{-8}\ c/ml}{2 \times 10^{-4}\ c/ml}\right] + \left[\frac{0.005\ \text{rem/yr}}{0.5\ \text{rem/yr}}\right] \right\rangle \left\langle 0.5\ \text{rem/yr} \right\rangle$$

$$\cong (0.005 + 0.02 + 0.0003 + 0.00045 + 0.01)\ (0.5\ \text{rem/yr})$$

$$\cong (0.036)\ (0.5)\ \text{rem/yr}$$

$$\cong 0.018\ \text{rem/yr}$$

So long as the sum of the fractions $(A_1 + W_1 + A_2 + W_2 + E_1)$ does not exceed unity, the permissible whole body dose rate will not be exceeded.

3. Similarly, the thyroid dose would be:

$$\left[\left(\frac{1 \times 10^{-11}\ \mu c/ml}{2 \times 10^{-9}\ \mu c/ml}\right) + \left(\frac{4 \times 10^{-7}\ \mu c/ml}{2 \times 10^{-5}\ \mu c/ml}\right)\right] \left[0.5\ \text{rem/yr}\right]$$

$$+ \left[\left(\frac{1 \times 10^{-11}\ \mu c/ml}{3 \times 10^{-10}\ \mu c/ml}\right) + \left(\frac{9 \times 10^{-8}\ \mu c/ml}{2 \times 10^{-6}\ \mu c/ml}\right)\right] \left[3.0\ \text{rem/yr}\right]$$

$$+ \left[\left(\frac{0.005\ \text{rem/yr}}{0.5\ \text{rem/yr}}\right)\right] \left[0.5\ \text{rem/yr}\right]$$

$$\cong [0.005 + 0.020]\ [0.5\ \text{rem/yr}]$$

$$+ [0.033 + 0.045]\ [3.0\ \text{rem/yr}]$$

$$+ [0.01]\ [0.5\ \text{rem/yr}]$$

$$\cong (0.013) + (0.23) + (0.005)$$

$$\cong 0.25\ \text{rem/yr}$$

IV. RADIOACTIVITY CONCENTRATION GUIDED RELATED TO USE

Radioactivity Concentration Guides for radionuclides in any environmental phase relate specifically to the manner in which that phase is employed by man. For example, the previously discussed RCG values for water standards for this purpose does not necessarily imply it meets acceptable standards for all uses.

A. Consider, for example, the consumption of aquatic life grown in waters containing certain specific radionuclides.

1. It has been reported(6) that if the concentration of P^{32} in the Columbia River were permitted to reach 2×10^{-4} μc/ml, (that is, about ten times the recommended RCG for individuals in the general population) fish obtained from the river would be unsafe for human consumption. If one pound of fish taken from such waters were consumed daily by an individual, the weekly radiation dose, at some seasons of the year, would approximate 200 rads (200 rems).(6) For this reason, an RCG of 3×10^{-7} μc/ml has been suggested for P^{32} in biologically populated waters.(7) This is roughly one seventieth of the current RCG for P^{32} in drinking water for individuals in the general population.

2. Another radionuclide in this same category is Na^{24}. Its RCG for drinking water for individuals in the general population is 4×10^{-4} μc/ml (assuming it is present in soluble form and the critical organ is the Total Body). For the protection of fish populations, an RCG of 2×10^{-6} μc/ml has been suggested.(7)

3. Data obtained by other investigators indicate that many of the same considerations apply to the establishment of RCG values for waters which serve as growing areas for clams, oysters, and other shellfish.(8)

B. Similar considerations apply to radioactive contaminants in air

1. Studies in Great Britain(9) (10) indicate that the presence of I^{131} in air can lead to significant contamination of garden produce, as well as pastures and milk supplies from cows fed in such areas. As previously listed, the RCG for this radionuclide in air to be breathed by individuals in the general population is 3×10^{-10} μc/ml. The British work indicates that, to assure the safety of milk supplies and garden produce, environmental air levels should be held to an RCG of approximately 7×10^{-13} μc/ml.

V. CONSIDERATIONS IN ENVIRONMENTAL SURVEILLANCE

The preceding discussion emphasizes the inter-relationship of the several environmental phases. If the air and water in a particular area contain radioactive materials, it is quite probable that significant contamination will be present in milk and foodstuff produced in that environment. Because public health officials must be in a position to evaluate the total radiation stress being placed upon man, and to do so they must know all sources of radiation exposure, measurements restricted to any one environmental phase will not be adequate. In fact, such a monitoring procedure could lead to a false sense of security, since the "obvious hazard is not always the "real" hazard.(1)

Thus, in the surveillance of streams which serve as an important source of seafood, biota samples may be just as important as the water itself. Similarly, the sampling of milk and foodstuffs will form a necessary part of air sampling programs if the overall radiation exposure originating through such contamination is to be evaluated. Because of the factor of biological concentration, it may well be that milk and foodstuffs will ultimately serve as the principal indicators of environmental radiation levels, water and air sampling serving mainly to determine the contamination source and to provide data enabling their contribution to be included in the overall radiation picture.

VI. SUMMARY

The sources of man's radiation exposure may range from one radionuclide contaminant in one environmental phase to multiple contaminants in multiple phases. The proper conduction of an environmental surveillance program demands an understanding of the fundamentals underlying the concept of Radioactivity Concentration Guides. Evaluation of the data obtained in such a program requires an understanding of present day approaches for assessing multiple radiation sources.

VII. REFERENCES

1. National Committee on Radiation Protection and Measurements, "Permissible Dose from Sources of Ionizing Radiation", Handbook 59, published by the National Bureau of Standards, (Sept. 24, 1954), Price 30¢. Also see Addendum to National Bureau of Standards Handbook 59 (April 15, 1958).*
2. Title 10, Part 20, "Standards for Protection Against Radiation", Federal Register, Volume 24, Number 86 (May 2, 1959.)
3. National Committee on Radiation Protection and Measurements, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure", Handbook 69, published by the National Bureau of Standards (June 5, 1959) Price 35¢.*
4. International Commission on Radiological Protection, "Recommendations of the International Commission of Radiological Protection", (Adopted September 9, 1958). Published by the Pergamon Press, Ltd. 4 and 5, Fitzroy Square, London, W. 1(1959).
5. News Release - National Bureau of Standards, "Summary of NBS Handbook 69, 'Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water'," (April 23, 1959).

*For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C.

Radionuclides in Terrestrial Food Chains

INTRODUCTION

Today, fallout from nuclear weapons tests is the most widespread source of radiocontaminants to the food chain. Many of the details as to how radioactive materials from this source move through the food chain and become deposited in the human population have been published in the scientific literature (see bibliography at the end of the outline) and were reported in whole or in part in the 1957 and 1959 Hearings of the Special Subcommittee on Radiation of the Congressional Joint Committee on Atomic Energy.

It is the purpose of this outline to present an over-all concept of the mechanisms involved in the transfer of radionuclides through the food chain, to indicate where the uncertainties and disagreements lie, and to emphasize newer data and their current interpretation.

HISTORY AND PURPOSE OF TERRESTRIAL STUDIES

Actual experimentation with fission products in farm animals was started as early as 1948 (Comar, et al.) in a program supported by the U.S. Atomic Energy Commission. Even though there was no recognition of the fallout problem as it now exists, there was at that time an intuitive feeling that more data about the behavior of the "bone seeking" fission products in the food chain should be obtained. Since that time, studies have been done with radioisotopes of strontium, cesium, iodine and others, using beef cattle, dairy cattle, sheep, swine, and poultry, in addition to laboratory animals. Although the Atomic Energy Commission has continued to support work in this area, other agencies in more recent years have also supported certain phases of this program. These agencies include the Department of Defense, the Department of Agriculture, and the Public Health Service.

Studies of the metabolism, movement and effects of fission products in the food chain may be of value in the following ways. Such studies:

a. Make possible the prediction of the relationships between the levels of radioactivity in the various steps within the food chain and the resulting levels in the human population.

b. Provide a means for evaluating ways by which the levels in the human population may be minimized.

c. Provide background information for setting up environmental sampling programs and for interpreting the data obtained.

d. Make available animal data which may be useful for estimating behavior of radionuclides in humans.

e. Make possible predictions of the possible effects of environmental contamination - especially in the grazing animal population.

Radionuclides of Importance in Environmental Contamination

As shown in Table 1, it is considered that iodine-131, barium-140, strontium-89, strontium-90, and cesium-137 will be of primary importance from the standpoint of hazard to the human population from fallout. Other radioactive substances are of lesser importance because of: (a) low fission abundance, (b) short half-life, and (c) non-entry into food chain. Before confining our interests to the radioisotopes listed in Table 1, however, a general comment or two may be in order.

Table 1

Radioisotopes of Importance in Environmental Contamination

	Physical Half-life
Iodine-131	8 days
Barium-140	13 days
Strontium-89	51 days
Strontium-90	28 years
Cesium-137	30 years

Radioactive materials that poorly absorbed by plants from soil and any that are poorly absorbed by animals from their feed may still reach the human diet as a result of consumption of vegetation carrying adsorbed radiocontaminants. Any hazard would result from exposure of the gastrointestinal tract of man to radiation from the unabsorbable material passing through. Experiments with goats and dogs have indicated that this exposure would be small compared to the simultaneous exposure from materials deposited within the body. The reasons are: (a) relatively rapid movement of substances through the gastrointestinal tract, (b) absorption of the radiation by the intestinal contents thus giving a shielding effect, and (c) the high probability that any radioactive substance adjacent to the mucosal tissue would be in contact with less active cells.

The problem of carbon-14 in the food chain has not been studied in detail. It would seem that the specific activity of carbon-14 in the vicinity of plants would ultimately be reflected as such in the carbon of the human body. In the event of rapidly changing carbon-14 levels, then one would have to consider the time lag in passage of carbon atoms from the vicinity of plants to the human population. Also, there is the matter of rates of carbon turnover. Work needs to be done along these lines, but these considerations appear to be of lower priority at this time.

Again, turning attention to Table 1, it is noted that iodine-131 and barium-140 have relatively short half-lives (8 and 13 days respectively); strontium-89, an intermediate half-life of 51 days, and strontium-90 and cesium-137 have relatively long-half-lives of 28 to 30 years.

Tables 2 and 3 indicate the metabolic behavior of these radioisotopes in the body. Iodine-131 is well absorbed, collects in the thyroid gland, and is fairly rapidly removed by physical decay and biological action. Barium-140 and the two radioisotopes of strontium are only partially absorbed, but most of that which is absorbed is deposited in the skeleton. Barium-140 rapidly disappears by physical decay, and strontium-89 in the skeleton decreases somewhat more slowly by the same process. Strontium-90 is slowly removed by physical and biological processes, and substantial amounts of any strontium-90 once deposited will be present throughout the life of the individual. The rate of removal would be faster in a growing individual than in a mature individual. Cesium-137 is well absorbed into the body, collects in muscle and other soft tissues, and enters cells in a manner similar to that of potassium. It is removed from the body by biological action with a half-time of removal that has been estimated at about 140 days in man.

Table 2

	Metabolic Behavior
Iodine-131	collects in thyroid
Barium-140	like calcium, collect in bone
Strontium-89	
Strontium-90	
Cesium-137	like potassium, collects in muscle

Table 3

	Removal Rate from Body
Iodine-131	fast
Barium-140	fast (physical decay)
Strontium-89	relatively fast (physical decay)
Strontium-90	slow
Cesium-137	relatively fast (biological half-time of 140 days)

THE FOOD CHAIN

Figure 1 presents a schematic diagram of the major terrestrial pathways by means of which environmental radiocontaminants can reach man. The following list of possible pathways sums the information in this diagram:

a. atmosphere to man

b. atmosphere to plant to man

c. atmosphere to soil to plant to man

d. atmosphere to plant to animal to milk to man

e. atmosphere to soil to plant to animal to milk to man

f. atmosphere to plant to animal to animal products to man

g. atmosphere to soil to plant to animal to animal products to man

Figure 1
Food Chains

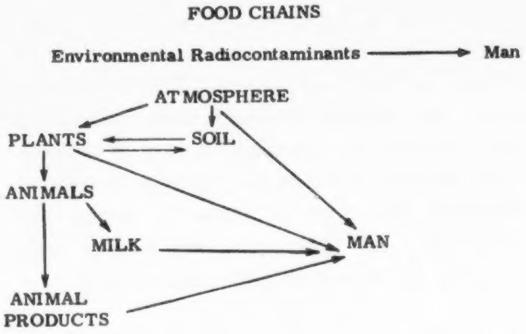

FOOD CHAINS
Environmental Radiocontaminants
Man
ATMOSPHERE
PLANTS
SOIL
ANIMALS
MILK
MAN
ANIMAL PRODUCTS

Figure 2 summarizes the pathways that are important for the various radioisotopes.

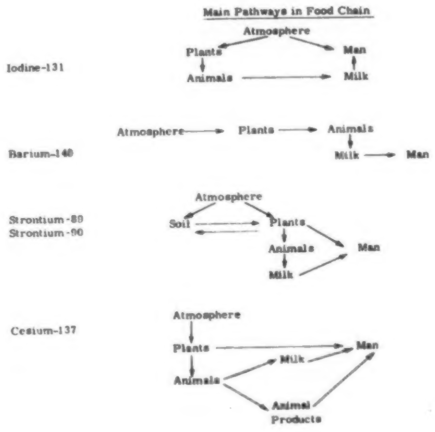
Iodine-131: Because of the relatively short half-life, the soil step is not important and only pathways (a) and (d) are significant.

Barium-140: Again, because of the short half-life only pathway (d) is significant.

Strontium-89, -90: Because of the low concentration in muscle tissue, the important pathways are (b), (c), (d), (e).

Cesium-137: Because cesium-137 is fixed in soil and markedly unavailable to plants, and because this radioisotope is deposited in both muscle tissue and milk, the important pathways are (b), (d), (f).

Figure 2


Main Pathways in Food Chain
Iodine-131
Atmosphere
Plants
Man
Animals
Milk
Barium-140
Atmosphere
Plants
Animals
Milk
Man
Strontium-89
Strontium-90
Atmosphere
Soil
Plants
Animals
Milk
Man
Cesium-137
Atmosphere
Plants
Man
Milk
Animals
Animal Products

Consideration of the most likely pathways enables an appropriate choice of environmental samples. These are summarized in Table 4. It is noted that milk is useful for analysis of all the radioisotopes listed. With iodine-131 and barium-140 the radioassay must be carried through before loss of radioactivity by physical decay. It follows from various physical and biological considerations that thyroid tissue is useful for monitoring of iodine-131 and whole body counting for monitoring of cesium-137.

Table 4

	Samples of Importance for Monitoring
Iodine-131	plants, milk, thyroid
Barium-140	plants, milk
Strontium-89 Strontium-90	soil, plants, milk, dairy products, bone, aquatic food
Cesium-137	plants, milk, dairy products, whole body

The matter of relative pathways in the food chain is extremely complex and Table 5 lists some of the factors that must be taken into account. Mention is made here of these uncertainties to emphasize the need for more of our agricultural experts to apply themselves to such problems.

a. Soil and climatic conditions: It is obvious that the soil characteristics, calcium level, terrain and meteorological conditions will have an important bearing on the amounts of various fallout contaminants that reach the plant via the soil, or that stay on the plant.

b. Plant cover: As an example, a heavy root mat may delay radiostrontium reaching the soil for dilution with soil calcium and lead to higher Sr*/Ca ratios in the plant than would otherwise be expected. (Sr* refers to any radioactive strontium).

c. Management: The levels of environmental contamination at various steps of the food chain in any given situation may well depend upon such factors as plowing and fertilization procedures and feeding practices (e.g., barn feeding, pasture, watering in shallow ponds).

d. Dietary habits and food technology: The actual amounts of radiocontaminants that reach the human body will depend upon such things as: (1) proportion of milk in diet, (2) amounts of leafy vegetables and extent of washing, and (3) use of frozen foods which are well washed.

e. Time pattern of contamination: At short times after production of radiocontamination, the shorter-lived radioisotopes such as iodine-131, barium-140 and strontium-89 may be of most importance. At longer times the strontium-90 and cesium-137 become more important. If contamination ceases, then the soil reservoir becomes of more importance and direct fallout on vegetation is minimized. Thus the relative importance of the atmosphere to plant pathway vs. the soil to plant pathway depends upon the accumulated soil reservoir as compared to the fallout rate at any given time.

Table 5

Factors That Determine Importance of Food Chain Pathway

1. Soil (e.g. calcium level)
2. Plant cover (e.g. heavy root mat may delay Sr reaching soil for dilution with soil calcium)
3. Management (e.g. plowing depth, fertilization, barn feeding vs. pasture)
4. Dietary habits (e.g. proportion of milk in diet)
5. Food technology (e.g. washing of frozen foods)
6. Time pattern of contamination (e.g. if tests were stopped, soil reservoir becomes more important).

Strontium-90 Relationships

Since strontium-90 is probably the most important of the environmental radiocontaminants, the remainder of the discussion will be mainly concerned with this substance.

We are interested both in the amount of strontium-90 (Sr^{90}) that reaches the population and the Sr 90/Ca ratio (strontium-90 to calcium ratio) as it is laid down in the human body. These quantities are interrelated; however, there are some advantages in dealing with Sr 90/Ca ratios. This is because exposure of the population occurs primarily by way of strontium-90 contamination of dietary calcium, and strontium metabolism generally parallels and is interrelated with calcium metabolism. The amount of calcium is also known; stable calcium values are invariably determined in experimental and survey work.

Table 6 presents data that have led to an important concept. According to the values for animals, it is clearly seen that if the animal is raised on a diet of 100 strontium per 100 calcium then the body of the animal will contain about 25 strontium per 100 calcium. The early data on rats were obtained by tedious incorporation of strontium-90 into the rat diet, and feeding animals on this contaminated diet for two to three generations. These results have been confirmed by independent methods and are generally accepted. It should be noted that this ratio can be changed by artificial conditions, but one is impressed with the constancy of this ratio on commonplace diets.

The values for man are particularly important and call for especial comment. Obviously, it has been impossible to do careful studies on numerous normal individuals as has been done with animals. Examination of the work that has been done leads to the conclusion that the reduction in Sr/Ca ratio in man under usual conditions is probably not less than two nor more than four; one group has recently reported a reduction of as high as 5.5 based on population studies. However, from the preponderance of data and from a conservative point of view, it is recommended that a reduction value of between two and four be used until more definite data are available (i.e. if the diet contains 100 Sr* to 100 Ca then the body of man would be expected to contain 25 to 50 Sr* to 100 Ca).

Table 6

Comparative Use of Strontium and Calcium

Diet		Body
100 Sr* - 100 Ca	rat	28 Sr* - 100 Ca
"	mouse	35 Sr* - 100 Ca
"	rabbit	22 Sr* - 100 Ca
"	sheep	24 Sr* - 100 Ca
"	goat	29 Sr* - 100 Ca
"	cow	18 Sr* - 100 Ca
"	man	50 Sr* - 100 Ca 25 Sr* - 100 Ca

Note: Observed Ratio = OR for rat = 0.28

Table 7 presents some information on two factors of some import that may change the discrimination against strontium relative to calcium. In rats, it has been definitely shown that very young animals do not discriminate as much against strontium. From limited studies on man, the discrimination in a 9 year old child was the same as measured in adults up to 73 years of age. However, we have no data on very young children and this is another reason for conservatism.

In rats, it can be seen that milk in the diet tended to reduce the discrimination against strontium. However, from limited studies with man, milk did not appear to show as marked an effect as it did with rats.

Table 7

Factors That Change Discrimination

Age			
	rats	15 days old	78 Sr* - 100 Ca
	"	194 days old	45 Sr* - 100 Ca
	man	9-73 yrs. old	no change
	"	infants	no data
Diet			
	rats	non-milk diet	28 Sr* - 100 Ca
	"	milk diet	57 Sr* - 100 Ca
	man	non-milk diet	44 Sr* - 100 Ca
	"	milk diet	54 Sr* - 100 Ca

Table 8

Processes That Discriminate Against Strontium

1.	Absorption from alimentary canal	- Large
2.	Urinary excretion	- Large
3.	Movement from blood to milk	- Large
4.	Movement from mother to fetus	- Large
5.	Movement between blood and bone	- Small
6.	Endogenous, biliary, pancreatic excretion	- Small

Table 9

Comparative Secretion of Strontium and Calcium in Fetus of Rat

Diet of Mother	Body of Mother	Body of Fetus
100 Sr* - 100 Ca	28 Sr* - 100 Ca	17 Sr* - 100 Ca

The physiological processes within the bodies of animals and man that are responsible for the differential behavior of calcium and strontium have been widely studied. The findings are illustrated in Table 8. In general, processes that involve physiological handling, and most likely active transport of calcium, are the ones that tend to move calcium in preference to strontium. The processes of known importance are: (a) absorption from the alimentary tract, (b) urinary excretion as a result of efficient tubular reabsorption of calcium and poor reabsorption of strontium, (c) secretion from blood into milk and (d) movement from blood of the mother to the developing fetus. These then are the processes that should be studied if one wants to alter artificially the differential behavior of calcium and strontium.

The Sr/Ca ratio that is developed in the fetus is shown in Table 9. It is noted that the diet of the mother rat contains 100 strontium - 100 calcium, the body of the mother contains 28 strontium - 100 calcium, and the developing fetus contains about 17 strontium - 100 calcium. Similar data have been obtained with rabbits, and strontium-90 survey data of human stillbirths confirm the idea that the fetus will have about one-half the Sr/Ca ratio of the mother.

The comparative secretion of strontium and calcium in the milk is very important from a practical standpoint. Table 10 shows that if the diet of the lactating cow or goat contains 100 strontium - 100 calcium, then the milk will contain about 11-12 strontium per 100 calcium. These findings have been confirmed many times and are generally accepted. We do not have values for human milk, and these would be helpful in evaluation of the body burden of strontium-90 that will develop in the breast-fed child. Arrangements are now in progress by the New York Health and Safety Laboratory of the Atomic Energy Commission to obtain actual data on mother's milk.

Table 10

Comparative Secretion of Strontium & Calcium in Milk

Diet		Milk
100 Sr* - 100 Ca	cow	11 Sr* - 100 Ca
100 Sr* - 100 Ca	goat	12 Sr* - 100 Ca
100 Sr* - 100 Ca	woman	?

It may be of interest to show what happens to the strontium-90 that is eaten by the dairy cow. As seen in Table 11, about 95% is excreted in the feces, about 1.5% in the urine, and about 0.9% appears in the milk. Each liter (or quart) of milk contains about 0.1% of the amount of strontium-90 eaten daily by the cow. These are results of a recent experiment on ten dairy cows, supported by the U.S. Department of Agriculture.

Table 11

Fate of Strontium-90 Eaten by Cow

Milk (% of daily dose/liter)	0.1
Milk (% of daily dose/day)	0.9
Feces (% of daily dose/day)	95
Urine (% of daily dose/day)	1.5

Effect of Dietary Calcium and Strontium on Strontium Metabolism

It seems important to have an understanding of factors that govern the movement of strontium in the food chain. The first consideration would naturally be the level of stable strontium in the diet. Experiments have shown, however, that levels of stable strontium in the feed of animals necessary to cause any significant decrease of ingested strontium 90 are detrimental.

The next step is to ascertain the effect of calcium levels. Table 12 shows the results of a study just completed on dairy cows and goats that had been placed on varying levels of calcium. It is noted that regardless of the level of stable calcium or strontium in the diet, there was obtained the same value of 9 - 12 Sr* per 100 Ca as compared to 100 Sr* - 100 Ca in the diet. The implications of this are indicated in Table 13. If a cow is fed a diet containing 100 strontium - 100 calcium then the milk will contain about 12 strontium - 100 calcium; according to the concept of the previous table, if the diet of that cow were supplemented with stable calcium to contain 100 strontium - 200 calcium, the behavior would be the same as for 50 strontium - 100 calcium, and the milk would contain only 6 strontium - 100 calcium. Table 14 gives the results of a relatively long-term study in which rats grown on a higher calcium diet accumulated a lower body burden of ingested radio-strontium than those grown on lower calcium diets.

Table 12

Effect of Calcium Level

Diet		Milk
	Cow	
100 Sr* - 100 Ca	Low calcium	10 Sr* - 100 Ca
"	Normal calcium	9 Sr* - 100 Ca
"	High calcium	11 Sr* - 100 Ca
"	High strontium	12 Sr* - 100 Ca
	Goat	
"	Low calcium	12 Sr* - 100 Ca
"	Normal calcium	12 Sr* - 100 Ca
"	High calcium	12 Sr* - 100 Ca
"	High strontium	12 Sr* - 100 Ca

Table 13

Implications of Raising Dietary Calcium

Diet	Milk
100 Sr^* - 100 Ca	12 Sr^* - 100 Ca
100 Sr^* - 200 Ca) 50 Sr^* - 100 Ca)	6 Sr^* - 100 Ca

Table 14

Effect of Dietary Calcium Level on Sr^* Retention

% Calcium in Diet	% of Ingested Sr^* in Rat
0.5	17.7
1.0	7.0
2.0	3.8

It must be noted that there is disagreement among workers about this sort of result. These arise mainly from experimental difficulties in evaluation of long-term effects from results of short-term studies. Active experimentation is underway, however, and the practical implications will one day be properly understood.

It should be emphasized at this point that from the standpoint of human nutrition there is no better recommendation than presently accepted practices. If ever necessary, it would be more practicable to modify the diet of the milk-producing animals than that of the human population.

Relationships Between Sr/Ca in the Vegetation and in the Human Population

It is possible to make some estimates of the relationships that will exist between the Sr/Ca ratio of the vegetation and that in the human population when steady-state conditions have been attained. We have chosen to use vegetation as a base because of the uncertainties and exceedingly long times that will be required for steady-state distribution to be attained in soil. At any given time, the relationships are best established by analysis of appropriate samples. Under future steady-state conditions, the relationships can be derived from studies of stable strontium to calcium ratios and the type of experimental work already described. At intermediate times, one can only modify the steady-state relationships by educated guesses from present day surveys.

Figure 3 presents an estimation of the relative contributions of calcium and radiostrontium from dietary constituents in the United States. It appears that the sources of dietary calcium are approximately as follows: 4% from cereals, 16% from other plant products, 75% from dairy products, and 5% from meat, fish, eggs, etc. It can first be noted that meat, fish and eggs contribute to the calcium and strontium content of the diet to only a small extent, and are therefore not considered further. If the plant material of the biosphere has the same Sr/Ca ratio, then milk while contributing 75% of the calcium would contribute only 45% of the radiostrontium; plant material would contribute about 20% of the calcium but 50% of the radiostrontium. It is emphasized, therefore, that under these conditions, the contribution of milk should be placed in proper perspective.

The same considerations are presented in a more usable form in Table 15. By multiplication (for each food contributor of calcium)

Figure 3

Contribution of Dietary Calcium and Sr^* to Man at Equilibrium

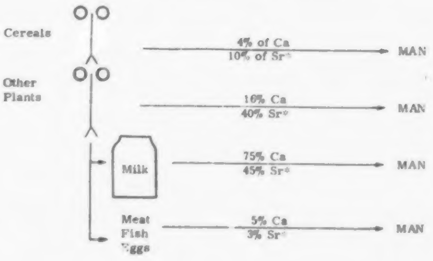


Table 15

Relations Between Sr* - Ca of Vegetation (100 Sr* 100 Ca) And Sr* - Ca of Man

	% of Ca from	Plant Product	Diet Body	Sr* per 100 Ca in body
Cereals	4	1	0.25	1.0
Other Plants	16	1	0.25	4.0
Dairy Products	75	0.12	0.5	4.5
Meat, Fish, Eggs	5	0.25	0.25	0.3
		Total Sr* per 100 Ca		10

of the following (a times b times c), one arrives at the contribution of each food item to the body in terms of amount of strontium per 100 calcium in the body, assuming again that all plant material contains 100 strontium per 100 calcium:

a. The percent of calcium that the food contributes

b. The biological discrimination factor in going from the plant to the food contributor.

c. The biological discrimination factor in going from the food as consumed to the human body

The first point is that one arrives at an overall reduction in Sr/Ca ratio of about 10 in going from the vegetation to the human body. This seems reasonably conservative; there is agreement that there is only a slight chance that the reduction factor could be as low as five or as high as twenty.

The data as arranged in Table 15 can easily be modified if there is some knowledge as to special conditions. For examples, if a child were getting 100% of its calcium from milk then it can be calculated that the strontium-calcium ratio in its body would be 6 strontium - 100 calcium instead of 10 strontium - 100 calcium (100 × 0.12 × 0.5 = 6). Similarly, these figures can be modified if, for example, the cereals average higher, and the vegetation that man eats average lower than the vegetation that the cow eats.

Table 16 presents two important situations. Because of placental discrimination against strontium, it is expected that the newborn would have about one-half of the strontium-calcium ratio existing in the blood of the mother during the period of fetal calcification. It should be remembered that it is the diet of the mother shortly before and during the gestation period that is the most important factor.

It is emphasized that breast feeding of the infant instead of using cow's milk will markedly lower the strontium-calcium ratio that is laid down in the infant. This is because of the added discrimination that takes place during passage of the calcium through the mother's body to the mother's milk.

Table 16

Relations Between Sr* - Ca of Vegetation (100 Sr* - 100 Ca) And Sr* - Ca of Newborn and 6 month old

I. (Sr* - Ca) of Newborn = 1/2 (Sr* - Ca) of Mother

II. Breast Feeding may decrease Sr* - Ca of young child by factor of 10 as compared with formula feeding.

Metabolism of Cesium and Potassium

The comparative metabolism of cesium and potassium have not been studied in as much detail as for strontium and calcium.

Some recent data, however, are presented. Table 17 shows the fate of these two elements when ingested by the dairy goat. About 6% of the ingested radioactive cesium appears in the milk; other work with dairy cows has given values of up to 13% appearing in the milk. Table 18 presents data on comparative metabolism of the two elements based on a diet of 100 cesium - 100 potassium. It is of interest to notice that there is a preferential secretion of cesium into milk as compared with potassium. The cesium-potassium ratios among tissues appear to vary considerably indicating that the comparative metabolic behavior is more complex than it is for strontium and calcium.

Table 17

Fate of Cesium-137 and Potassium Eaten by Goat

	Potassium	Cesium
Milk (% of daily dose/day)	4.4	6.0
Urine	35	21
Feces	6	32

Table 18

Comparative Metabolism of Cesium and Potassium in Goat

Diet		
100 Cs - 100 K	Milk	140 Cs - 100 K
"	Whole Body	90 Cs - 100 K
"	Muscle	50 Cs - 100 K
"	Ovary	120 Cs - 100 K
"	Kidney	360 Cs - 100 K

Possibilities of Reducing Strontium-90 Levels

The possibilities of minimizing strontium-90 movement in the food chain by treatments of soil have been discussed by others. Practical steps to reduce the strontium-90 burden in the population by procedures with man and animals would require considerable research along nutritional and physiological lines. The following are suggested as possible approaches for further work; none are now practicable.

a. Use of uncontaminated calcium to contribute a maximum proportion of the dietary calcium of animals and man.

b. Increasing the biological discrimination against strontium relative to calcium.

c. Avoidance of surface-contaminated vegetation of thorough washing.

d. Use of plants low in calcium relative to calorific value.

e. Increasing the intake of uncontaminated calcium, primarily in milk-producing animals.

f. Removal of strontium from food products.

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Behavior of Radionuclides in Food Chains

Fresh Water Studies

INTRODUCTION

Fresh water lakes and streams, in their traditional roll of receiving and transporting all manner of materials, seem destined to continue this function in the atomic age and have added to their burden limited amounts of radionuclides. In many cases the water may serve as an effective medium through which the nuclides can become incorporated into living organisms. Ultimately some of the radioactive materials may be deposited in fish or crops which are eaten by man and thus provide an additional source of radiation exposure.

This discussion is primarily directed toward the mechanisms through which aquatic forms may accumulate radioactive materials from their environment and the manner in which we may expect certain nuclides to become distributed in biological systems of fresh water lakes and streams. In a broad sense, the subject of the behavior of radionuclides in fresh water food chains might also include irrigated crops, and animals which drink from streams and ponds. Such problems, are, however, more closely allied with terrestrial studies and in this case consideration will be given only to those forms which actually live in the water.

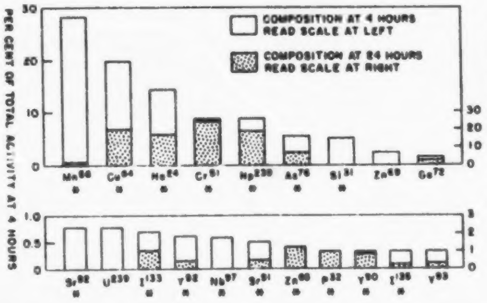
SOURCES

Fresh water streams may receive radioactive materials from a great variety of sources. Naturally occurring radioisotopes removed from the atmosphere and eroded from radioactive ores have been carried in both surface and underground waters since early in the history of the earth. Typically, U^{238}, Ra^{226}, and Th^{232} are present in measurable amounts, but other isotopes such as K^{40} and C^{14} are also present. The background levels are in the range of 10^{-9} to 10^{-10} $\mu c/ml$ for most surface waters(1) but values in excess of 10^{-4} $\mu c/ml$ have been reported for certain hot springs of high radium content. In most streams the natural concentration of the heavy metals is so low and their uptake by aquatic forms is so small that they contribute but little to the radioactive content of the organisms. Most of the natural radioactivity in the biota originates from K^{40} which, in fish, amounts to about 3×10^{-6} $\mu c/g$.

With the creation of a demand for large amounts of uranium as a basic source of nuclear energy the uranium ore refining industry has expanded rapidly during the past decade. As pointed out by Tsivoglou, et al.(2), the concentrations of radioelements of the uranium-radium family are substantially increased in streams which receive the effluent directly from uranium mills or seepage from ponds used to retain their tailings. The concentration of radium in the biota of the streams is likewise increased.

Liquid wastes from the fabrication of refined uranium into fuel for reactors can be another source of naturally radioactive isotopes to streams. In comparison with releases at the mills and with the problems which accompany irradiation of the fuel, however, the contribution from the fabrication plants will usually be quite insignificant.

Figure 1



RADIOELEMENT CONTENT OF REACTOR EFFLUENT 4 HOURS AND 24 HOURS AFTER IRRADIATION. (Radioelements marked * ore are routinely measured).

The large quantities of artificially radioactive nuclides produced in reactors form a new type of disposal problem, the handling of which requires a technology considerably more complex than that associated with the natural isotopes. Dependent upon individual design, the reactors themselves may or may not contribute significant quantities of radionuclides to fresh water streams. The megacurie quantities of fission products which accumulate in the reactor fuel do not, under ordinary circumstances, escape from the fuel while it is in the reactor. As pointed out by Terrill(3), "Present practice involves extensive control measures through design and operation to confine the fission products within the reactor core and its immediate environs". Failure of the cladding of fuel elements does, of course, provide the opportunity for entry of fission products into the primary coolant stream or moderator. Under normal circumstances, the principal source of radioactive materials in the fluids which pass through the reactor core is the activation of materials which are exposed to the neutron flux. These activation products may originate from materials dissolved in the coolant or they may corrode from the surfaces of the fuel elements, cooling system, or structural materials. In the Hanford-type reactor, the coolant is filtered Columbia River water which is returned to the river after a single pass through the reactor. Figure 1 shows the isotopes which predominate in effluent from the Hanford reactors four hours after irradiation. Many of these have such short half-lives that they have decayed to very low levels by the end of the first day. Minor amounts of fission products are also found in the Hanford reactor effluent not only as a consequence of the occasional failure of a fuel element, but also because of natural amounts of fissionable uranium in the Columbia River water. The release of radioactive effluent to the Columbia River is accompanied by extensive monitoring, both before and after discharge, in order to provide assurance that the radiation exposures to people who subsequently use the river or eat fish or irrigated crops are well within permissible limits.

The kinds and amounts of radionuclides discharged to the Columbia River with the Hanford reactor effluent should not be considered as characteristic of other types of reactors. The concentrations of various activation products which build up in the primary circulating fluid will be dependent upon the intended chemical composition of the fluid, impurities present, the corrosion of cladding on fuel elements, piping and vessels, film formation, neutron energy and flux, radioactive half-life, and the effectiveness of ion-exchange "clean-up" loops where these are used. Significant amounts of activation products of common elements ranging from tritium to neptunium can conceivably be present. In most cases there probably will not be intentional release of radioactive materials accumulated in the re-circulated fluids directly to

"Radioactive Waste Management Operations at the Hanford Works", included in Congressional Hearings on Industrial Radioactive Waste Disposal (1959).

fresh water streams. However, minor leakage from the complex piping and fuel handling systems into the plant effluents appears almost inevitable.

Excluding nuclear detonations, the largest potential source of radionuclides to the environment is the fission products which accumulate in reactor fuels. At the present time, the bulk of the high-level waste which results from the processing of the fuel elements, is confined in some artificial or natural container. Even so, large quantities of water with low or intermediate concentrations of radionuclides result from the later stages of most separation processes and these must usually be disposed of at, or very near, the processing plant. In many cases, disposal of such wastes will be to the ground or to pits on the surface in order to take advantage of the ion-exchange capacity of the soil and the time lags which allow for decay of the isotopes with short and intermediate half-lives. At the Hanford plant the cumulative volume of intermediate-level waste discharged to the ground through 1958 amounted to nearly 4 billion gallons, containing nearly 2 million curies of beta-emitters. The topography, soil structure, and geology at Hanford favor retention and none of this material has been detected in the Columbia River(4). Conditions for surface disposal are less favorable at other existing major installations, and wastes containing fission products discharged to pits at both Oak Ridge(5) and Chalk River(6) have seeped through the soil and appeared in streams and lakes which receive the drainage.

Radioactive wastes may also enter fresh water streams via the drains from industrial, medical, or research facilities which use isotopes. Although the amounts involved are comparatively small, such sources should not be entirely disregarded since the Oak Ridge National Laboratory is now shipping on the order of 150,000 curies of isotopes a year to domestic users.

On the basis of high yield from nuclear fission, significantly long half-life, and biological importance, the fission products which one would expect to find in greatest abundance in the biota of fresh water streams and lakes are: Sr^{89}, Sr^{90}, Y^{91}, $Zr^{95} + Nb^{95}$, Ru^{106}, I^{131}, Cs^{137}, Ba^{140}, Ce^{144}, and one or more rare earths. In addition to these, neutron activation products which appear to be of importance include: P^{32}, Sc^{46}, Cr^{51}, Mn^{54}, Fe^{55}, Fe^{59}, Co^{57}, Co^{60} and Zn^{65}. In the immediate proximity to reactors, very short-lived isotopes such as Na^{24}, Cu^{64}, and As^{76} may be detected.

As a result of the use of nuclear energy, the associated mining and refinement of fissionable materials, and the widespread use of radioisotopes, the radioactivity in a few surface waters of the world has now been increased above the original background level. As the use of atomic energy and its byproducts becomes more extensive, the numbers of rivers and lakes which receive radionuclides will increase, and the organisms which inhabit these waters will also acquire the radioactive materials. Some appreciation of the mechanisms involved in the uptake of radionuclides by aquatic organisms is necessary to anticipate potential sources of exposure to man, and, if necessary, to effectively control or reduce the amounts accumulated.

UPTAKE BY LIVING ORGANISMS

Radioactive materials present in the water may be taken up by aquatic organisms via three different mechanisms: 1. adsorption onto exposed surface areas, 2. absorption through membranes exposed to the surrounding water, possibly with the aid of active transport mechanisms, and 3. engulfment of food or inert particles which contain the nuclides. The relative importance of these mechanisms is different for various kinds of organisms and even similar species. It also fluctuates widely between different elements and different environments.

Adsorption, which is a physical process, occurs very rapidly. It is of greatest significance among those organisms which have large surface to volume ratios such as sponge and diatoms. A clear distinction between adsorption and biological absorption is not easy to make however, since the physical process of adsorption may be a necessary primary step in the movement of ions into the cell. Films of bacteria and other microorganisms may also fix radioactive materials on the surfaces of organisms to give an adsorption-like effect.

The process of absorption is obviously of prime importance to the plants since this is the means by which nutrient materials are removed from solution and metabolized. Many non-essential elements will also enter the plant cells because of passive diffusion through the membranes or because the organism is handling them in a manner similar to the essential elements. The uptake of radioactive materials by the plants is, of paramount importance to the higher forms since the plants form the food base.

Direct absorption of some radioisotopes from the water also occurs in aquatic animals, including the fish, with the gill membranes probably playing the important role. Such direct uptake by fresh water fish has been demonstrated for Sr^{90} (7) (8) (9), Ba^{140} + La^{140} (7), Ca^{45} (10) (11) (12), P^{32} (13), Na^{24} (7), and Cs^{137} (14). However, the dominant means by which many radioactive materials are accumulated by aquatic animals is through ingestion, since this is the manner in which they obtain the bulk of their nutrient materials. Ingestion does not insure that the isotope will be assimilated through the gut. Some materials may pass through the gut with virtually no uptake, and seldom, if ever, will all of the ingested radioactive material be metabolized. For example, Watson(15) found that after 24 hours, rainbow trout retained about 60 percent of the radiophosphorus which they ingested. Schiffman(16) found that only about 7 percent of Sr^{90} incorporated into natural food organisms was retained by trout after one day.

CONCENTRATION FACTORS

The uptake of radionuclides by organisms is obviously not a phenomenon which is peculiar to the radioactive forms of the elements. Rather, the radioisotope acts only as a tracer to demonstrate the difference between the abundance of the element in the water and in the organism. The so-called "concentration factor"

$$\frac{(\mu c/g \text{ of organism})}{(\mu c/ml \text{ of water})}$$

for any radionuclide cannot exceed the ratio which exists between the concentrations of the element in the organism and in the water. On this basis it should be possible to predict the ultimate concentration factors for various radionuclides from conventional quantitative chemical measurements, provided the nuclide has become distributed throughout the system and is uniformly mixed with its stable counterpart. In practice, however, it may be quite difficult to measure the concentration of some elements because of the minute quantities involved.

Estimation of concentration factors for fresh water organisms involves, at the present time, a considerable amount of speculation. While the concentration of some elements in a variety of marine organisms is available,(17) and the chemical composition of sea water is relatively stable, there is very little information readily available on the chemical composition of fresh water organisms. Chemistry of various lakes and streams differs so greatly from one region to another that no generalizations can be made. The picture is clouded further by the fact that the concentration of many elements in aquatic forms is partially dependent upon their abundance in the surrounding water. Although it is virtually impossible to write down probable concentration factors which will apply to more than one locality, an indication of the differences in the orders of magnitude of the concentration for a few of the common elements in some organisms and in water is shown in Table 1.

Table 1

Concentration (μg/g wet weight or ml) of some elements in fresh water organisms and in some major rivers of the United States

Element	Organism[1]			Water[2]	
	Algae (Spirogyra)	Insect Larvae (Caddis fly)	Fish (Minnows)	Low	High
Silicon	1,500	20	10	3	20
Sodium	1,500	700	1,000	1	200
Phosphorus	250	400	6,000	<0.001	1.5
Calcium	1,500	300	3,000	2	200
Iron	6,500	300	1	<0.01	6.0
Strontium	2	0.2	0.3	0.006	1.9

[1] Values are only estimates of orders of magnitude obtained by spectrophotometric analysis at the Hanford Laboratories. They are recorded here to illustrate differences which can exist and are not intended for use in precision work.

[2] Abstracted from Moyle, J. B., "Relationships between the chemistry of Minnesota Surface Waters and Wildlife Management". Journal of Wildlife Management 20: 303-320, 1956; and Clarke, F. W., "The Composition of the River and Lake Waters of the United States". U.S. Geological Survey, Prof. Paper 135, 1924. Strontium values from Alexander, Nusbaum, and MacDonald, "Strontium and Calcium in Municipal Water Supplies", A.W.W.A., Journal 46(7): 643-654, (1954).

It is evident then, that radioisotopes of the different elements will be concentrated to various amounts by the different organisms. The concentration of phosphorus in Columbia River water is about 0.01 ppm, while in the fish it amounts to about 6,000 ppm. These values would lead to an estimated concentration factor of about 600,000 for the fish. Since radiophosphorus is one of the isotopes present in the effluent which is discharged into the Columbia River from the Hanford reactors, the actual concentration factor for this nuclide can be measured. In contrast to the theoretical value of 600,000, the maximum observed value is only about 100,000. The observed value is less because the biological processes required to deposit and exchange the phosphorus in the body of the fish are long in comparison to the radioactive half-life of P^{32}, which is about 14 days. Consequently, the radioisotope is not uniformly mixed with all of the stable phosphorus involved in the system. Such a reduction would not be expected for long-lived isotopes.

From measured amounts of radionuclides in the effluent from Hanford reactors and in organisms living in the Columbia River immediately below the reactors, concentration factors have been calculated for the more abundant isotopes. These are listed in Table 2 for the season when maximum values occur.

The concentration factors for As^{76}, Sc^{46}, Cr^{51}, and Cu^{64} are quite low in fish in comparison to those in algae and insect larvae. This illustrates that food chains, which on the one hand provide the mechanism for transferring radioactive materials from one organism to another, can also serve, in some cases, to reduce the concentration of radionuclides in large animals. Two different processes can be involved. Where possible, the organisms will eliminate non-essential elements, and thus there will be a repeated selection against such nuclides along the food chain; and short-lived isotopes will decay to low levels as they pass through the chain.

Table 2*

Observed Concentration Factors $\left(\frac{\mu c/g \text{ of organism}}{\mu c/ml \text{ of water}}\right)$

For Significant Isotopes Found in Columbia River Organisms

Isotope	Algae[a]	Insect[b] Larvae	Fish[c]
P^{32}	100,000-1,000,000	100,000	100,000
Zn^{65}	100,000	10,000	1,000-10,000
Cs^{137}[d]	1,000-5,000	1,000	5,000-10,000
Sr^{90}	10,000	100	1,000
Na^{24}	100	100	100-1,000
As^{76}	10,000	1,000	100
Sc^{46}	100,000	1,000	10
Cr^{51}	100-1,000	100-1,000	10
Cu^{64}	10,000	1,000	10

Many of these values are not yet well defined and are subject to revision.

[a] Stigeoclonium sp. [b] Hydropsyche sp. [c] Richardsonium sp.

[d] Data for Cs^{137} obtained from a pond environment rather than the Columbia River and species are different from those listed above.

(Values are based partly on data reported by J. D. Davis, R. W. Perkins, R. F. Palmer, W. C. Hanson, and J. F. Cline[18] and R. C. Pendleton and W. C. Hanson[19].)

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*This table reproduced from "The Need for Biological Monitoring of Radioactive Waste Streams," by R. F. Foster presented at the Nuclear Engineering and Science Conference April 6-9, 1959, Cleveland, Ohio.

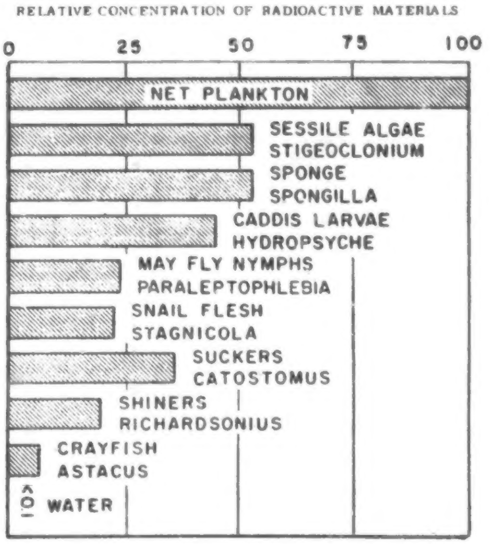
The isotopes which are most likely to have high concentration factors in fish and other large aquatic animals are those which are readily assimilated, which are retained for relatively long periods of time in various body structures, and which have long radioactive half-lives. These are characteristics which result in relatively high body burdens for humans as well, and which influence a low maximum permissible concentration for the isotope, in drinking water or food.

DIFFERENCES BETWEEN SPECIES

Differences in the concentration factors for various isotopes among different species leads, to different levels of radioactivity in the organisms. Columbia River organisms provide a good example of this as shown in Figure 2. The short-lived isotopes contribute significantly to the activity density (quantity of radioactive materials per unit mass of substance) of plankton, algae, and sponge. But in the higher animal forms, about 95 percent of the activity originates from P^{32}.

Figure 2

Radioactivity in Different Columbia River Organisms

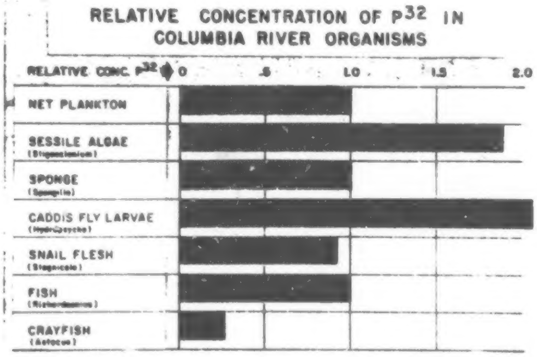


Davis and Foster, "Bioaccumulation of Radioisotopes through Aquatic Food Chains", Ecology 39: 530-535 (1958)

Because of the dominance of the P^{32}, it is of interest to consider this isotope separately from the others. Figure 3 shows the relative concentrations of P^{32} in most of the species included in Figure 2. The different concentrations result from a combination of several factors: the chemical composition of the various species is different, the moisture and organic content varies, and there are different lag times along the food chain which permit radioactive decay.

As mentioned before, the reduction in the concentration of a radioisotope of an essential element along the food chain may occur with relatively short-lived isotopes because the ratio of radioactive to non-radioactive atoms of the element does not remain constant throughout the entire biological system. This ratio may properly be called the specific activity since it is the concentration of the isotope per gram of stable element - in this case - μc P^{32} per gram of P^{31}. The Columbia River below the Hanford reactors provides an unusual opportunity for the study of the specific activity of P^{32} in various organisms of the food chain, since a near steady state is maintained. A "fresh" supply of the isotope is added to the river water at a more or less

Figure 3

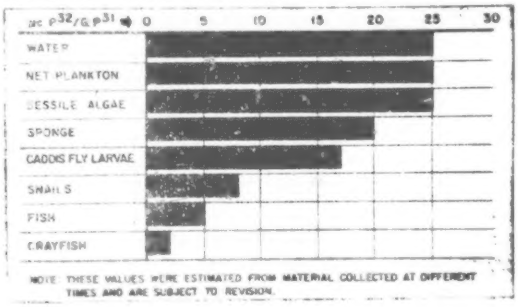


constant rate with the reactor effluent. Since the concentration of stable phosphorus in the river water is also relatively constant, the specific activity of P^{32}, remains about the same in the water throughout much of the year. If there were a near instantaneous and complete exchange of phosphorus between the river water and all aquatic organisms, then the specific activity of the organisms would be identical with that of the water. Figure 4 shows that this is not the case. For plankton and sessile algae the specific activity is virtually the same as in the water. This indicates a very rapid exchange of phosphorus between these forms and the water. The specific activity is progressively less in the insect larvae, snails, fish, and crayfish (scavengers), indicating that replacement of phosphorus in these animals goes on at a relatively slow rate, and thus the phosphorus "ages" in the organism.

If one compares the specific activity of caddis fly larvae with that of their food, which is predominantly plankton for the species represented here, it can be shown that the average phosphorus atom remains in the caddis larvae for about 9 days.

The low specific activities of P^{32} in the larger animals results not only from slow phosphorus exchange within the animals, but also from the reduced specific activity of its food. The effect is thus cumulative along the food chain. For isotopes which are shorter lived than P^{32}, the reduction in specific activity along the food chain may be even more spectacular; for isotopes with relatively long half-lives the reduction may not be apparent. It must be remembered, however, that a reduction in specific activity along the food chain results from a combination of two factors: one is a comparatively short half-life, and the other is a relatively long retention of the element in the organisms.

Figure 4


SPECIFIC ACTIVITY OF COLUMBIA RIVER ORGANISMS

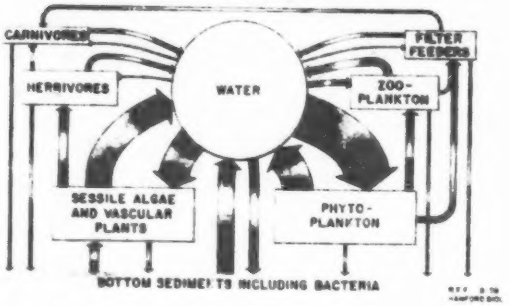
NOTE: THESE VALUES WERE ESTIMATED FROM MATERIAL COLLECTED AT DIFFERENT TIMES AND ARE SUBJECT TO REVISION.

EXCHANGE BETWEEN ORGANISMS

Although we talk in terms of food chains with the implication that radionuclides and other materials are transferred sequentially from small food species to larger predatory forms, such simple, straight-forward systems are not strictly characteristic of aquatic communities. Such communities might better be thought of as complex chemical exchange systems in which there is a kind of equilibrium established between the concentration of the nuclide in the water and in the various biological forms, silt, and other exposed surfaces. Several experiments have been carried out in both the laboratory and the field with the use of P^{32} in order to measure the rates of exchange between various components of the systems(20-31). Figure 5 is a highly schematic representation of the kind of phosphorus exchange which operates in a fresh water community. The size of the arrows is intended to give some conception of the quantity of phosphorus (or radiophosphorus in this case) moving in a given direction in some short unit of time. A large fraction of the available isotope moves rapidly back and forth between the water and the photosynthetic plants. Animals which eat the plants obtain an appreciable part of their radiophosphorus from the plants, but they also carry on at least some exchange directly with the water.

Figure 5

EXCHANGE OF RADIOPHOSPHORUS
BETWEEN WATER AND BIOTA


CARNIVORES
FILTER FEEDERS
HERBIVORES
WATER
ZOO-PLANKTON
SESSILE ALGAE AND VASCULAR PLANTS
PHYTO-PLANKTON
BOTTOM SEDIMENTS INCLUDING BACTERIA

A similar arrangement exists at the higher trophic levels. Each of the groups of organisms contributes some isotope to the sediments, either through death or via fecal pellets, with bacteria playing an important role in decomposition. Some of the isotope remains with the sediments and, in time, is buried deeper. However, much of it is released back into the water and recycled through the biota.

In many fresh water communities the greatest mass of material will be made up of the photosynthetic plants - the primary prodecers which constitute the first trophic level. The mass of successive trophic levels will usually be smaller and smaller, so that relatively few carnivorous fish are supported at the top of the biomass pyramid. However, in some open-water communities where the primary trophic level is made up almost exclusively of phytoplankton, with a rapid "turnover", a part of the pyramid may be inverted,(32). Of the total inventory of radiophosphorus and most other radionuclides, one would expect to find the greatest fraction held in those organisms which make up the greatest portion of the biomass. In fresh water systems this will usually be the green plants, which also have rapid exchange rates and an affinity for a large variety of nuclides. Nevertheless, only a small fraction may be held in the large fish, this may well be the part of greatest interest to the radiation protection specialists.

It should be evident then, that radioisotopes of biologically essential elements, when introduced into streams or lakes, are not apt to remain exclusively in the water. Rather, they will rapidly become distributed between the water, the biomass, and the sediments: In many cases the portion which is removed from the water will exceed that which remains. If it is desired to reduce the specific activity of a contaminating radionuclide by adding carrier to the water, consideration must be given to the probability that there is a greater reservoir of essential elements in the solids (including the biota) than is dissolved in fresh water.

SEASONAL VARIATIONS

Where continued or repetitive release of radioactive waste occurs, a true equilibrium in distribution of radionuclides between water and organisms will seldom be attained. Even under stable conditions of flow and effluent discharge, seasonal fluctuations in the composition and metabolism of the community will keep the system in a dynamic state. New blooms of plankton or vascular plants will create a demand which will draw material from the water and from other parts of the biomass. Conversely, the dying-off of large masses of vegetation may release significant quantities of radionuclides back into the water where they will be available to other components of the community.

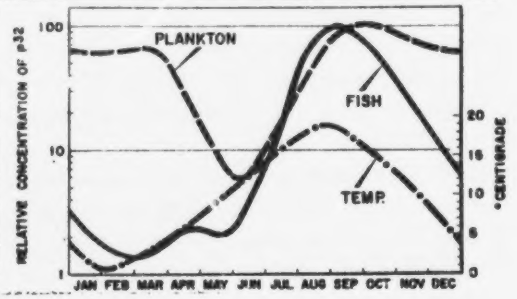
Most aquatic animals are cold blooded, and thus their metabolic rates change with variations in temperature and so, with the seasons. Concentrations of those radionuclides affected by metabolic rates in aquatic organisms will also fluctuate with the seasons. During the cold-water period food intake is drastically reduced. If ingestion is the principal mode of uptake of a radionuclide, the supply to the animal will likewise be reduced, and the quantity of nuclide in the animal will diminish as a result of radioactive decay and biological elimination. The reverse is true when temperatures are high.

Figure 6 shows a smoothed curve for the activity density of plankton and small fish of the Columbia River over the period of a year. Fluctuations in the plankton (predominantly diatoms), are quite similar to those in the water since there is a rapid exchange of nuclides between the water and the plant cells by direct absorption and adsorption; temperature has little effect in this case.

A pronounced decrease in the activity density of the plankton occurs during the late spring, because the flow of the Columbia River increases greatly at this time to provide additional dilution of the effluent from the reactors. Fluctuations in the activity density of the fish are on the other hand, more closely related to temperature. As indicated above, the marked increase in activity density of the fish during the time of high temperature reflects an increase in metabolic rate all along the food chain. Not only are the fish eating more food, but each food organism has become more radioactive, and the effective retention time for radioactive decay within each trophic level has become less. The effect is thus cumulative along the food chain.

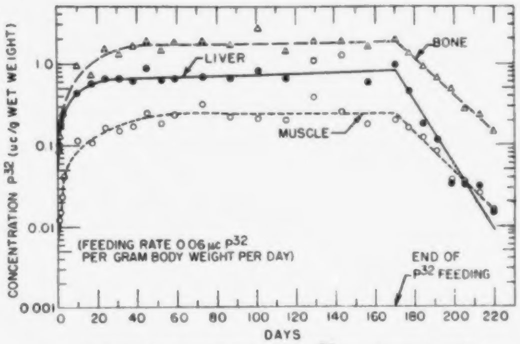
Figure 6

SEASONAL VARIATIONS IN THE CONCENTRATION OF P^{32} IN COLUMBIA RIVER PLANKTON AND FISH



Because of the rapid exchange of some nuclides between the water and algal cells, the activity density of these organisms will rapidly reflect changes in the concentration of the radionuclides in the water. However, the uptake and elimination of most nuclides in the larger forms, such as the fish, is a comparatively slow process. Their activity density will then fluctuate in a rather sluggish manner in comparison to changes in the water or in their food. Figure 7 shows that trout fed a ration of P^{32} each day required about 2 weeks to reach an equilibrium level. The activity density of the fish may not therefore, provide a good indication of the conditions in the water at the time fish are collected. What may be more significant however, is that the fish samples may provide a reasonably good index of the average conditions which have existed in the water over a period of hours or even weeks, dependent on the particular nuclide involved.

Figure 7



UPTAKE AND RETENTION OF P^{32} BY TROUT TISSUES

CONCLUSION

Radionuclides which enter fresh water streams and lakes may enter the food chain and thus appear in fish and other aquatic forms eaten by man. The radioactive contamination levels which are apt to result in the various organisms, are affected by a large number of physical, chemical, and biological factors. For radioisotopes of some of the more abundant essential elements, we can estimate within broad limits what the maximum levels may be. The characteristics of fresh water communities vary so greatly between different localities however, that the continued release of substantial quantities of radionuclides must be carried out with considerable prudence and with monitoring of the concentrations of radionuclides which actually result in the environs at the point of release.

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Additional plates by L. G. Williams, Aquatic Biologist, Basic Data Program, SEC.

Pollutant Radionuclides in the Marine Environment

I. INTRODUCTION

The oceans of the world are of great value to man. They provide important transportation in world trade, furnish sites for recreation, and are a source of minerals. After desalting, they even may be an important source of fresh water for areas now facing serious water shortage situations. Most important of all, the oceans supply man with important foods and many marine products. There is now great concern that pollution of the sea with radioactive materials may seriously affect man's use of the sea by curtailing his use of its living resources.

II. THE MARINE ENVIRONMENT

A. Harvest Areas

The areas of the oceans are vast and cover the greater part of the surface of the world. Although there are important high seas fisheries, most of the commercial important marine organisms are harvested in coastal waters or in offshore waters not very far from land. It is in these areas close to land that the great influx of materials from runoff occurs and where pollution with wastes is most likely.

1. INTRODUCTION OF RADIATION

Radioactive materials entering the sea may be accumulated by seafood organisms and returned to man. To evaluate and understand possible return of radioactivity from different sources, it is necessary to follow the behavior of pollutant radionuclides when added to the marine environment.

B. Constitution of Sea Water

An aquatic environment is quite unlike a terrestrial environment, and a marine environment has characteristics different from those of fresh water.

1. RICH IN ELEMENTS

Sea water likely contains all the known elements, many present in relatively high concentrations. The great abundance of certain elements tends to lessen the importance of the addition of radionuclides of these elements as regards uptake of radioactivity by the biota.

2. SUSPENSION IN A SOLUTION

Also, natural sea water is truly a suspension. It contains particles of various sizes, both living and non-living. The abundance of particles, as we shall see, is of prime importance in the availability of nutrient chemicals and elements to marine animals. It is likewise of great importance in the uptake of many radionuclides.

III. LINKS OF THE FOOD CHAIN

A. Phytoplankton, the Primary Source

Marine animals are ultimately dependent on the photosynthetic activity of green plants (Figure 1). In the sea the light necessary for this process is limited to the uppermost water mass. For the great expanse of the open oceans, the green plants of the upper few hundred feet serve as the primary source of food for all the animal life. These are the minute algae. Their small size assists in

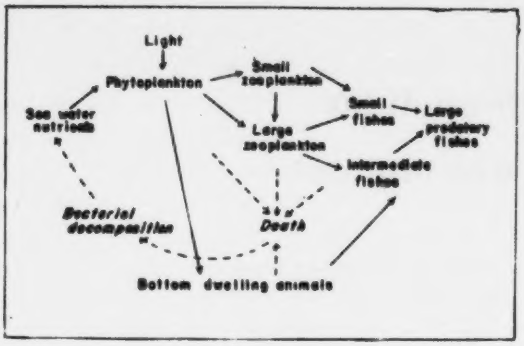

Figure 1

General scheme of nutrient cycle in the sea

preventing their sinking to the darker lower levels and provides a large surface area for the direct absorption of the nutrient chemicals which are present in the water in dilute amounts.

1. INDIRECT PLANKTON UTILIZATION

For the most part, the larger marine animals and fishes are not able to feed on these small plants. They are dependent on other animals possessing feeding mechanisms enabling them to utilize the minute plant cells. We have, therefore, a vast number of small animals of the plankton that feed on the phytoplankton directly. These in turn, may serve as food for many of the larger animals and fishes. Some fish, however, feed on smaller fish, and still others on bottom-dwelling animals. These animals on the bottom are themselves dependent on the plankton, either as living organisms or as organic particles following their death and settling to the bottom. Some bottom forms feed on other bottom-dwelling animals, but all are ultimately dependent on the phytoplankton of the upper water layers.

B. "Chain" Is a Complex Web

Generally the food chains of the animals of the sea are not simple. It is perhaps more descriptive to speak of these complexities as a food web. The complexity of the food web is realized when one considers the variety of organisms constituting the diet of different fishes and the various chains involved in the feeding of each of the food organisms itself.

1. MANY FACTORS CHANGE SPECIES' DIETS

The chain is further complexed by the fact that the type of organisms eaten by the fish changes at different periods in its life history. The availability of particular foods also changes with different seasons. It is evident that radionuclides may pass through food chains to our commercially important fishes. Some may enter from the water directly, and some may enter the food chain at different levels.

2. WHAT DETERMINES UPTAKE

Uptake depends on the elemental composition of the different organisms making up the food chains and the availability of radioactive material. It is readily apparent that it is difficult to follow accumulation and passage of radionuclides through the many steps of a complicated food chain.

IV. SOURCES OF RADIOACTIVE POLLUTANTS ADDED TO MARINE ENVIRONMENTS

A. Radionuclides From Several Sources

Pollution of marine waters can result from many different activities. There is no doubt that atomic warfare involving coastal waters or estuaries could cause great contamination of seafoods with radioactive materials. However, other problems would be of much greater immediate concern. Long-term fallout from the use or testing of nuclear weapons creates more hazardous situations to man from the use of foods produced on land than from those from the sea. However, there are measurable amounts and increasing quantities of the radionuclides of fission products entering estuaries and the sea from land run-off.

B. Wastes From Peacetime Projects

Although pollution of sea water can result from atomic warfare or from the testing of atomic weapons, the production and uses of atomic materials by man for peaceful purposes is becoming an important source of radioactive contamination of marine environments. These wastes originate chiefly from reactor fuel processing; operation of research, power, and production reactors; and utilization of radioactive materials in hospitals, industrial plants, and scientific research laboratories (see Chipman, 1959b).

1. CLASSIFYING RADIOACTIVE WASTES

Wastes may be classified on the basis of their radioactivity, for it is their level of radioactivity which governs their handling and their disposal. One may consider high-level radioactivity as that which requires considerable shielding to protect persons nearby. Intermediate-level radioactivity also requires shielding and care in handling, but wastes of this level may be decreased in radioactivity by reasonable storage and decay or by chemical treatments which allow their disposal as low-level wastes. Low-level wastes require only a minimum of care in handling and usually can be released to the environment with dilution and dispersion.

C. Land Reactors Cause Most Problems

It is in connection with reactor operation that the greatest problems in the disposal of radioactive materials are encountered. We are all familiar with fission process in a chain reaction and the formation of fission products. These must be separated from the unfissioned uranium fuel at intervals and it is therefore necessary to remove the fuel elements from the reactor after a certain time of irradiation for chemical processing. Also, to prevent excessive heat, reactors are cooled by air, water, liquid chemicals, or by other media having suitable properties. In the reactor core the coolants are exposed to neutrons and, as a result, different radioisotopes are formed dependent on the element composition of the coolant.

1. HIGH-LEVEL MATERIAL DISPOSAL DIFFICULT

At the present time there has been no satisfactory solution of the problem of disposal of high-level radioactive wastes, most of which originate in the reprocessing of nuclear reactor fuels to recover unused fuel elements.

a. Storage Not the Answer

Continued containment and tank storage is troublesome and costly, and the volumes to be handled are rapidly increasing. There is always a danger that escapement to man's environment may take place, a serious threat considering the high radioactivity of these wastes.

b. Ocean Depths Not Proved

Disposal of high-level wastes in great ocean depths has been considered. This does not appear to be a satisfactory solution for a number of reasons. Handling and transporting to areas of great ocean depth would have problems and would be costly. Also, we do not know the ability of the oceans to absorb such radioactive materials without creating hazards following dispersion. We would need to know more of the turnover times of deep waters, ocean currents, and of the possibilities of hazardous conditions arising in the utilization of seafoods and other marine products.

2. LOW-LEVEL WASTES STILL ONLY MINOR PROBLEM

Because of the volumes involved and the widespread origin of low-level radioactive wastes, it is obvious that dispersion in man's environment is necessary. At the present levels of production of such low-level wastes, disposal is not considered to be a major problem. However, new developments may alter the picture somewhat as time goes on.

a. Disposal Program Elementary

In the United States there is no programmed disposal of low-level radioactive wastes into marine waters excepting the placing of packaged solids or solidified liquids at a few designated sites. These wastes are generally of very low radioactivity and have a varied radionuclide composition. They arise chiefly from the use of radioisotopes in medicine, research, and industry. The disposal areas currently in use are well offshore and have a depth of about 1,000 fathoms. They appear to be perfectly safe and adequate for our present needs for disposal of this type of waste.

b. Direct Discharge Common

There are a number of large reactor installations and chemical plants for processing spent reactor fuels from which low-level liquid wastes are released directly into marine waters. The best known is the Windscale Works in England which discharges wastes into the Irish Sea. Additional plants are being constructed in Great Britain, and a processing plant is nearing completion in Sweden which will discharge wastes into the Baltic. It is likely that the number of such installations with sea disposal of wastes will continue to increase. Smaller reactor installations are also being built on sea coasts and the shores of estuaries.

D. Ships and Upcoming Source

Reactors of nuclear-powered ships can be an important source of contamination with certain radionuclides.

1. FISSION PRODUCTS LARGELY CONTAINED

The major radioactive waste products produced in the operation of nuclear reactors on ships are the fission products. These would be contained largely in the spent fuel elements and be removed from the ship at the time of refueling.

2. NEUTRON ACTIVATION PRODUCTS OFTEN DISCHARGED

Additional wastes result from the induced radioactivity of corrosion products in the primary coolant, together with small amounts of fission products which may be transferred to the primary coolant as a result of minor failures in the cladding of the fuel elements. The amount of radioactive materials in the primary coolant is maintained at relatively low levels by use of a bypass purification system resulting in the accumulation on ion exchange resin of corrosion product radioactivity and a considerably smaller amount of fission-product radioactivity. Discharge of volumes of the primary coolant during warm-up of a pressurized water reactor and disposal of ion exchange resins are the chief potential sources of radioactive contaminants to a marine environment from nuclear-powered ships.

V. RADIONUCLIDE COMPOSITION OF SEA POLLUTANTS

If we examine the radionuclide composition of the different radioactive wastes entering the marine environment, we find certain ones that may be considered of particular biological interest. These include some of the fission products and a few radioisotopes of the trace metals.

A. Rare Earth Group Predominates

From examination of Table 1, we find those fission products contributing most to the total radioactivity up to about three years of age are radioisotopes of the rare earth elements, or those having chemical characteristics similar to rare earths. Because of their long physical half-life, Sr^{90} and Cs^{137} are of considerable importance. In instances of pollution of marine waters with fission products, of particular concern are Sr^{90}, Cs^{137}, Ru^{106}, Zr^{95}, Nb^{95}, and Ce^{144}.

Table 1

Per cent of total radioactivity contributed by certain fission products of biological interest at different times after fission.[1]

	20 days	90 days	1 year	3 years	10 years	20 years
Sr^{89}	5.0	10.5	2.7	-------	-------	-------
Sr^{89} - Y^{90}	-------	-------	3.7	17.4	44.0	48.0
Y^{91}	5.6	12.5	3.8	-------	-------	-------
Zr^{95}	5.9	14.7	7.2	-------	-------	-------
Nb^{95}	2.3	18.0	14.7	-------	-------	-------
Mo^{99}	1.3	-------	-------	-------	-------	-------
Ru^{103m}	4.4	7.2	0.8	-------	-------	-------
Rh^{103}	4.2	7.0	0.8	-------	-------	-------
Ru^{106} - Rh^{106}	-------	-------	4.9	6.0	-------	-------
I^{131}	5.6	-------	-------	-------	-------	-------
I^{132}	1.1	-------	-------	-------	-------	-------
Cs^{137} - Ba^{137m}	-------	-------	2.9	13.6	36.0	45.0
La^{140}	13.9	1.8	-------	-------	-------	-------
Ba^{140}	12.0	1.6	-------	-------	-------	-------
Ce^{141}	9.7	8.5	-------	-------	-------	-------
Pr143	12.0	11.2	2.6	-------	-------	-------
Ce^{144} - Pr^{144}	2.6	12.0	52.8	42.0	-------	-------
Nd^{147}	5.0	-------	-------	-------	-------	-------
Pm^{147}	-------	-------	5.7	19.0	16.0	3.4
Sm^{151}	-------	-------	-------	1.1	2.5	2.6

[1] Adapted from data of Hunter and Ballou (1951). Reference, Chipmen (1958).

B. Metals Are Important

Besides these fission products, radionuclides of metals are of importance in pollution of the sea. Radionuclides of different metals were present in relatively high amounts in the biota following the tests of nuclear weapons in the Pacific. Almost half the radioactivity of tuna caught following the tests was due to an accumulation of zinc-65. In the giant clam there was a great accumulation of cobalt-60 (Weiss et al, 1956). Also, corrosion-product radionuclides are present in reactor coolant water of nuclear-powered ships and may enter marine waters. Important ones (Table 2) are Co^{60}, Fe^{59}, Cr^{51} and Ta^{182}. They are present in more concentrated amounts on the ion exchange resins used with ship reactors.

Table 2

Estimated amounts of important radioisotopes in reactor coolant water of the N.S. Savannah.[1]

Isotope	Concentration (μc/ml)
Corrosion Products	
Co^{60}	1.2×10^{-2}
Fe^{55}	1.1×10^{-2}
Fe^{59}	5.5×10^{-4}
Ta^{182}	1.7×10^{-2}
Cr^{51}	4.0×10^{-2}
Fission Products	
Sr^{90}	1.4×10^{-7}
Zr^{95}	1.4×10^{-6}
Ru^{106}	0.9×10^{-5}
Cs^{137}	1.5×10^{-4}
Nb^{95}	1.3×10^{-6}
Ce^{144}	0.8×10^{-6}

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[1] From Table 3, Publ. 658, NAS-NRC, 1959.

VI. STATE OF RADIONUCLIDES IN SEA WATERS

The physical states in sea water of some of the elements having radionuclides known to be present in wastes are shown in Table 3. For the more important fission-product radionuclides, only those of cesium and strontium are likely to be present in ionic form. Ruthenium, zirconium, niobium, yttrium and the rare earths are probably present chiefly as particles. Of the metals important in pollution, copper and zinc are likely present in ionic form while iron and cobalt occur as solid phases.

Table 3

Probable physical states of elements in sea water.[1]

	Percentage in given physical state		
Element	Ionic	Colloidal	Particulate
Cesium	70	7	23
Iodine	90	8	2
Strontium	87	3	10
Antimony	73	15	12
Tellurium	45	43	12
Molybdenum	30	10	60
Ruthenium	0	5	95
Cerium	2	4	94
Zirconium	1	3	96
Yttrium	0	4	96
Niobium	0	0	100

[1] From Greendale and Ballou, 1954.

A. Where the Wastes Go

Several things can happen to radioactive materials introduced into the sea as liquid wastes. They may remain in solution or be precipitated out, depending on whether or not the solubility product of the least soluble compound in sea water has been exceeded. Dissolved substances may also be precipitated by coprecipitation with other elements or by sorption on organic or inorganic particles already present in the sea. Such particulate matter in the sea will tend to settle to the sea bottom, although the rate of settling may be quite slow. However, even particles of colloidal sizes become associated with other particles present in the water. As pointed out previously, particle filtration is one of the basic means of passing elements through the food chains in the sea.

1. FALL AND BIOTIC UPTAKE LOWER WATER CONTENT

Characteristically, the addition of a radioactive pollutant to sea water is followed by a disappearance of the radioactivity from the water. There is marked uptake by bottom materials and by the biota. This uptake is so great that, even with repeated additions, water concentrations remain very low. For the most part, the accumulation of pollutant radionuclides in fishes results from concentrations in their food organisms and not from the sea water directly.

VII. ACCUMULATION OF RADIONUCLIDES BY THE BIOTA

A. Marine Phytoplankton

The small phytoplankton are noteworthy for their concentrating ability for most all the pollutant radionuclides. They are thus able to pass concentrated amounts of radioactivity to small marine animals and to fishes.

1. PICK UP MOST FISSION PRODUCTS

We have detected in the ash of phytoplankton cells nearly all the radionuclides present in the fission-product mixture added to the water in which they are grown. They had taken up ruthenium-106, cerium-144, yttrium-91, strontium-89, strontium-90 and yttrium-90. The presence of zirconium-95 and niobium-95 was indicated. Rare earth radionuclides are accumulated many thousands of times above sea water concentrations, as shown from the concentration factors for cerium-144 listed in Table 4. There is also immediate and great uptake of ruthenium-106, and also of yttrium-91.

Table 4

Concentration factors of Ce^{144} for various species of planktonic algae, calculated on a wet weight basis.[1]

Algae	Number of times over sea water concentration	
	After 0.5 hours	After 24 hours
Cateria	314	2422
Platymonas	1843	2127
Nitzschia	518	1970
Thallassiosira	2610	3346
Amphidinium klebsi	3001	4498
Porphyridium	802	3344

[1] From Rice and Willis, 1959.

2. ABSORPTION IS IMPORTANT

Much of this uptake and accumulation is related to surface absorption.

3. STRONTIUM, CESIUM, LARGELY REFUSED

The radioisotopes of strontium are not markedly accumulated by many species of marine plankton (Rice, 1956). Marine fishes and shellfish normally obtain their supply of strontium and calcium from the water directly. Both of these elements are present in sea water in rather large amounts. Also, marine phytoplankton do not appear to concentrate cesium-137 to any appreciable extent. Table 5 shows that none of the species tested had a concentration factor, based on wet weight, greater than 3.1.

Table 5

Concentration of cesium by marine algae.[1]

Algae	Concentration factor[2]
Bacillariaceae	
Nitzschia closterium	1.2
Amphora sp.	1.5
Nitzschia sp.	1.7
Chlorophyceae	
Chlamydomonas sp.	1.3
Carteria sp.	1.3
Chlorella sp.	2.4
Pyramimonas sp.	2.6
Nannochloris atomus	3.1
Rhodophyceae	
Porphyridium cruentum	1.3

[1] Boroughs, Chipman, and Rice (1957).

[2] The concentration factor is reported as the ratio of Cs^{137} in the algae (wet weight) to that in an equivalent weight of sea water at an apparent steady-state condition.

4. TRACE-ELEMENT COLLECTORS

Phytoplankton are important in passing the trace elements of sea water to animal forms. Although some may enter the bodies of fish and shellfish directly from the water, they are present in sea water at very low concentrations. Pollutant radionuclides of trace metals of sea water would normally follow the same pattern of uptake as the elements themselves. We have observed a rapid and extensive uptake of Zn^{65}, Co^{60}, and Fe^{59} when present in the sea water in which marine phytoplankton cells were suspended. It is obvious that, if these radioactive materials were present in sea water as contaminants, high concentrations would be found in the phytoplankton and could be passed to animals using these cells as food.

B. Marine Zooplankton

The small primary consumers in the sea play a very important part in passing nutrients to fishes. These minute animal forms possess filtering mechanisms which allow them to feed on phytoplankton. They are eaten by small fishes which may serve as food for others still larger. The small animal plankton are an important link in passing radionuclides accumulated by phytoplankton to fishes or other animals in the sea.

1. We have observed that marine copepods and other filter-feeding zooplankton forms do rapidly become radioactive when exposed to sea water in which are suspended radioactive phytoplankton cells and other radioactive particles. High concentration factors can result when such accumulation of radioactive food can be collected from large volumes of water.

a. Many Nuclides Just Pass Through

As regards the fission-product radionuclides which are present as particles or associated with the phytoplankton food, the great majority are those poorly absorbed from the digestive tract. Consequently, the accumulation of radioactivity by the filtering zooplankton is related to the presence of radioactive particles on the filtering mechanisms and concentrated within the digestive tract. They fail to accumulate significant amounts of fission-product radionuclides in their tissues.

b. Trace Metals Enter Tissues

Radionuclides of the trace metals, however, are made availabe in high concentration by particle filtration and readily pass through the walls of the digestive tract. We have observed that radiozinc and radiocobalt are taken up rapidly by marine copepods and that these are concentrated to high levels.

c. Sr^{90} and Cs^{137} Go Into Chain

Zooplankton may accumulate radionuclides present in the water in ionic form. If accumulated to any marked extent, appreciable concentrations may be passed to fishes using these forms as food. Two important fission-products radionuclides that may be considered in this connection are strontium-90 and cesium-137. A few species of zooplankton have calcareous structures and may concentrate strontium. Many species do not. We have measured concentration factors for radiostrontium of about one for the copepod, Tigropus, and less than one for the brine shrimp, Artemia (Figure 2). When phytoplankton food is present, however, a concentration of particles filtered from the water with concentrations of strontium may give an apparent concentration factor somewhat greater than one, particularly if the factor is calculated per unit volume of water disregarding the abundance of phytoplankton cells. Cesium-137 is slowly concentrated through a slow accumulation.

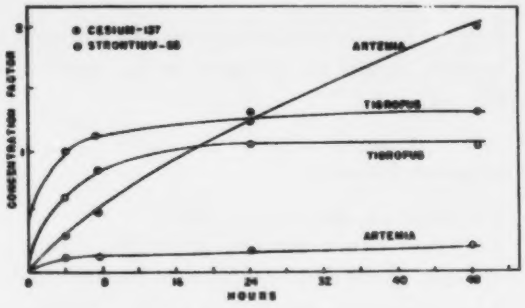

Figure 2

Accumulation of cesium-137 and strontium-85 by the copepod. Tigropus californicus, and the brine shrimp. Artemia salina, maintained in filtered sea water containing the isotope.

C. Bottom-Dwelling Invertebrates

1. IMPORTANT FOODS IN VULNERABLE HABITATS

Oysters, clams, and scallops are important fisheries organisms of our coastal and inshore waters, particularly within estuaries. They filter large volumes of water and feed on the small plant cells or organic particles which settle to the bottom. Accordingly, radionuclides present in the water in the form of particles are concentrated markedly. Often the greater part of the measured accumulation is due to association of particles with body surfaces and their presence in the organs and structures connected with the digestive tract. However, in pelecypods there is intracellular digestion with the taking in of food particles by phagocytic action. This may allow an accumulation of radionuclides not readily absorbed from the digestive tract by animals having extracellular digestion.

a. Mollusc AND Contents Eaten

The fact that man eats the whole soft tissues of oysters and clams allows for the ingestion of many radionuclides not incorporated into the tissues of these shellfish.

Strontium radioisotopes are taken up by shellfish, the uptake being primarily from the water. Strontium is concentrated only in their shells. There is no concentration of strontium in the soft tissues. Figure 3 shows the accumulation of radiostrontium by hard clams.

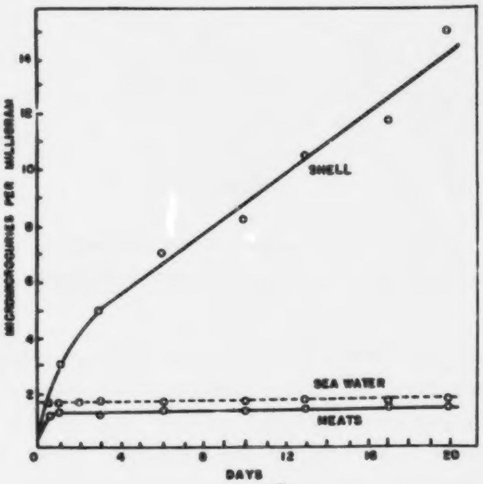

Figure 3

Uptake of strontium-85 by young hard clams, Mercenaria mercenaria.

b. Mollusc Tissues Avid Concentrators

Cesium-137 is accumulated to relatively high levels in the soft tissues of shellfish (Figure 4). There is a more rapid uptake by the soft tissues other than muscle, but the highest concentrations are reached in time in the muscles. Clams concentrate cesium-137 to a greater extent than do oysters, which agrees with differences in the amount of muscle tissue present in the two forms. The highest concentrations in the scallop are in the adductor muscle, which is the only body tissue eaten by man in this country.

Oysters, clams, and scallops contain very high concentrations of zinc and can concentrate Zn^{65} to extremely high levels (Chipman

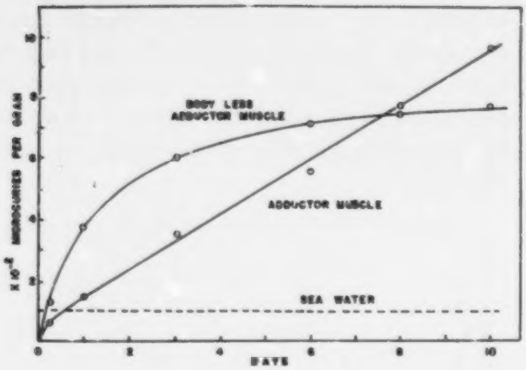

Figure 4

Uptake of cesium-137 by the body tissues of the bay scallop. Pecten irradians.

et al, 1958). They also concentrate radionuclides of other metals very markedly. Great concentrations of Co^{60} and Fe^{59} have been observed. Of the different marine organisms, the great concentrating ability of shellfish for many pollutant radionuclides is noteworthy.

2. CRUSTACEANS ABSORB LITTLE BUT CESIUM

Only small amounts of the radioactivity of mixed fission products administered entered the body tissues of edible crabs and shrimps. Of that that did enter, the greater part was present in the internal organs. Daily oral doses to the blue crab resulted in a gradual accumulation of radioactivity in the shell and in the edible muscle. In these crustacean shellfish, there is an accumulation of strontium radioisotopes in the shell and other calcified structures. Molting results in the loss of the concentrated radioactivity. We have found no concentrations of radiostrontium in the muscles. Cesium-137 is concentrated to relatively high levels in the edible meats. In the practice of "heading" of shrimp for market, the accumulated radioactivity of the internal organs and a major part of the shell is discarded. However, relatively high concentrations of radioactive cesium would be present in the marketed portion.

D. Marine Fishes

1. GENERAL ABSORPTION PATTERNS

Marine fishes absorb only small amounts of most of the radionuclides of fission products taken into the digestive tract. Cerium-144 was poorly absorbed from the tract when administered to croakers. Menhaden fed phytoplankton cells containing ruthenium-106 took up only about one per cent of the radionuclide (Table 6). Repeated daily doses of mixed fission products to fish resulted in a marked concentration of strontium-90 in the bones and scales, and a gradual accumulation of radioactivity in the body muscles from cesium-137. The greater part of the radioactivity of the internal organs was due to rare earth radionuclides. We have found from repeated doses of cerium-144 to croakers that the early concentration in the liver is followed by an accumulation in bone.

Table 6

Radioactivity of menhaden after feeding on phytoplankton cells containing Ru^{106}.[1]

(Tissues of 5 fish analyzed for each observation)

Time in hours	Per cent of dose			
	Gills	Digestive tract and contents	Remainder of fish	Total in fish
0	0.64	92.39	0.76	93.79
2	0.05	80.09	1.00	81.14
4	1.13	21.15	0.53	22.81
8	0.06	7.99	0.34	8.39
16	0.08	8.50	0.56	9.14
32	0.02	5.23	0.22	5.47
64	0.02	1.48	0.26	1.76
128	0.01	0.05	0.25	0.31

[1] From Chipman, 1959a.

2. STRONTIUM LOW, IN EDIBLE PARTS

Of particular interest to man is the accumulation of radioactive contaminants in the edible body muscles of marine fishes. For nearly all radionuclides the muscles have much lower concentrations than do other body tissues. There is no concentration of strontium radioisotopes in the edible body muscles of marine fishes. In an experiment with the killfish, Fundulus heteroclitus, for example, the body muscles had a concentration factor over water for strontium-85 of only 0.15 after exposure for 32 days (Figure 5).

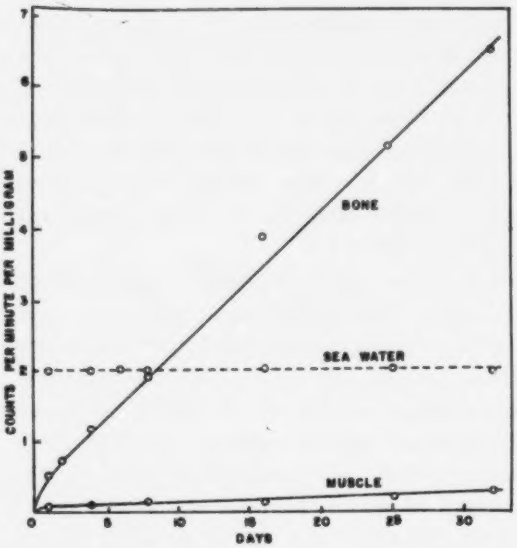

Figure 5

Accumulation of strontium-85 in muscle and bone of the killfish. Fundulus heteroclitus.

3. MUSCLES PICK UP CONSIDERABLE CESIUM

Cesium-137 is accumulated in the edible fish flesh. The rate of uptake is more rapid in internal organs than in muscles, but the long-continued uptake in muscle tissues results in significantly high concentrations. The concentration of cesium-137 in the body muscles of Fundulus at 72 days was about 35 times that of the water. In other tests using young spot, the concentration of cesium-137 in the muscles after 5 months was 23 times that of the water.

4. ZINC, COLBALT, IRON ACCUMULATE

Marine fishes were found to take zinc-65 into the body tissues very rapidly with accumulation in the bone, integument, and muscle tissues. High concentrations of zinc-65 were present in the internal organs, notably in the kidneys. There is a very long retention time for a part of the accumulated zinc-65. They accumulate cobalt-60 and iron-59 following uptake of the radioisotopes in their foods.

VIII. CONTROL OF SEA DISPOSAL OF ATOMIC WASTES

To prevent serious contamination of seafood organisms with radioactive materials, adequate control measures need to be exercised. Pollution of the sea with radioactive materials is taking place, and will continue. It is necessary to determine and to maintain safe levels of contamination. What is urgently needed is a more complete understanding of what constitutes safe levels of contamination.

A. USA Federal Practice

In the United States, control of the disposal of radioactive wastes is exercised by the federal government through the Atomic Energy Commission. Disposal has been kept to a very low level and limited to packaged solid wastes at a few sites well offshore.

B. Inshore Waters a Possibility

With expansion in the atomic energy industries and the more widespread use of radioisotopes, the need for disposal of greater amounts of this type of waste economically by private disposal companies at a greater number of locations is developing. In view of this, the Atomic Energy Commission asked the Committee on Oceanography of the National Academy of Sciences-National Research Council to study the feasibility of disposing of low level packaged radioactive wastes into the inshore waters of the United States. This committee will recommend locations that can be used safely as disposal areas, together with the limitations on quantity and kinds of radioactive materials, rates of disposal, and other pertinent factors necessary to keep the concentration of radioactive substances within permissible levels. If suitable areas are found, strict monitoring of the disposal operations will be done. A report on possible locations along the Atlantic and Gulf Coasts has recently been made (Publ. 655, 1959).

C. International Interests Involved

Disposal of high-level radioactive wastes in the sea is an international problem and has been the subject of discussion by individuals at international meetings. It is the subject of discussion at meetings of the different nations called by the International Atomic Energy Agency whose headquarters are in Vienna. It is likely that if sea disposal is done, the nations will follow the procedures that will be drawn up by this agency.

1. NUCLEAR SHIP WASTES ARE SPECIAL CASE

Radioactive waste disposal from nuclear-powered ships is also a matter of international concern and one that is urgently in need of control. Proposals have been drafted by several nations regulating disposal practices and these have been the subject of several meetings of the International Atomic Energy Agency. The proposal of the United States is given in a recent publication of the Committee on Oceanography of the National Academy of Sciences - National Research Council (Publ. 658, 1959).

2. UNIFORM INTERNATIONAL POLICIES SOUGHT

Disposal of low-level wastes, and particularly of liquid low-level wastes has been controlled individually by the different nations. This is generally controlled by the governmental agencies, although the operations often are carried on by private companies. The private companies themselves have been active in studying the problem of the effects of atomic waste disposal on the use of the sea as applied to their particular situation. The advice of scientists of various universities and research institutions is sought and considered. The most active nations in this field have been the U.S.S.R. and Great Britain, Norway, Sweden, Belgium, and France. Recently the nations of Northwest Europe have joined in an organization to work together in problems of the processing of spent reactor fuels and of disposal of radioactive wastes.

Countries of the British Commonwealth and still others throughout the world are rapidly developing their activities in the use of radioactive materials and are becoming increasingly aware of the problems of the disposal of atomic wastes. Although each country may be responsible for its own policies of waste disposal in the sea where other countries are not involved, it seems likely that recommended practices will be formulated by the International Atomic Energy Agency.

a. Safety is Prime Concern

All policies developed regulating sea disposal of radioactive wastes and all monitoring operations are based on safe disposal practices. Much depends on the marine scientists, the oceanographers, and the fisheries scientists in ascertaining what constitutes safe disposal to assure that hazardous situations do not develop affecting man's utilization of his ocean resources.

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Radionuclide Composition of Environmental Samples

I. INTRODUCTION

Efficient qualitative and quantitative analysis by gamma spectroscopy necessitates a knowledge of what radionuclides should be expected for given types of environmental samples. In order to evaluate the more biologically significant radionuclides, the total radionuclide composition of the sample must be known.

This outline will discuss the method of production of radionuclides and the expected radionuclide composition of environmental samples when contaminated by various sources.

II. METHODS OF PRODUCTION

The significant radionuclides in the environment are neutron-induced fission products, neutron-activation products, and naturally radioactive nuclides. Although some radionuclides are produced by such processes as proton activation, they are not a general environmental problem and so will not be considered here.

A. Neutron-Induced Fission Products

Fissioning is a process in which a heavy nucleus breaks up into two nuclei of intermediate weight. The majority of the newly formed nuclides, termed primary fission products, are radioactive and most of these undergo a series of decays giving rise to a large number of secondary fission products. There are over thirty modes in which the uranium-235 nucleus can undergo neutron-induced fission. There are over sixty primary fission products and the decay chain products total about two hundred nuclides. As an example, if one atom of uranium-235 undergoes neutron-induced fission, it can yield yttrium-95, iodine-138, two neutrons, and fission energy. Typical fission-yield curves for the neutron-induced fissioning of uranium-235, uranium-238, and plutonium-239 are shown in Figure 1. (1)

Not all fission products can be analyzed by gamma spectroscopy. Strontium-90, the most hazardous fission product, is a pure beta emitter which decays to yttrium-90 and then to stable zirconium-90. While yttrium-90 does emit a gamma photon, its low gamma abundance makes its use unfeasible for gamma spectral analysis of environmental samples. Some of the other

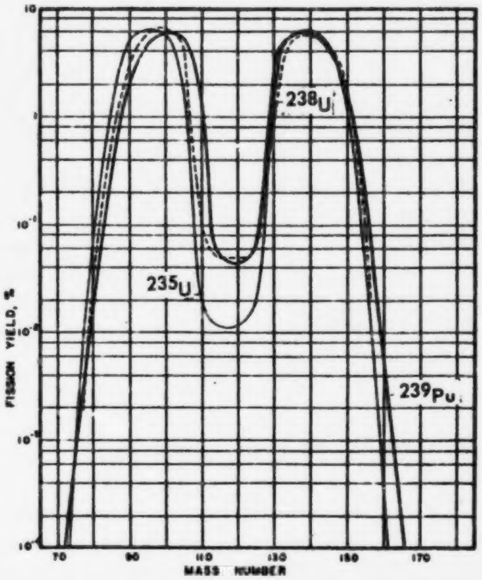

Figure 1.--Fission Yields for Slow-Neutron Fission of ^{235}U, ^{238}U, ^{239}Pu

fission products are also pure beta emitters or have gamma abundances too low for gamma spectral analysis.

B. Neutron-Activation Products

Atoms of most elements, when exposed to slow neutrons, capture them to form a radioactive species of the same element. The probability of neutron activation or cross-section (susceptibility) differs for the various stable nuclides. The neutron activation of construction materials of the reactor or weapon, coolant water or air, water or air impurities, and surroundings such as the earth in surface weapons tests can produce considerable quantities of radionuclides. These radionuclides may then contaminate the environment.

C. Natural Radioactivity

Some naturally radioactive materials were produced during the formation of the earth. Those with sufficiently long half-lives exist today. Other naturally radioactive materials continue to be produced by cosmic ray interactions. Members of the heavy element decay series and potassium-40 are examples of the first class, whereas carbon-14 and tritium are examples of the second class. The identification and quantification of natural radionuclides is generally difficult due to their low levels. An additional problem is their interference in the determination of man-made radionuclides.

III. SOURCES OF CONTAMINATION

A number of sources of environmental contamination will be surveyed to determine what radionuclides one would expect to find in appropriate environmental samples.

A. Normal Reactor Operations

A reactor is an apparatus in which nuclear fission is sustained in a self-supporting chain reaction. It includes fissionable material (fuel) such as uranium, moderating material to thermalize neutrons (except for a fast reactor), and a reflector to decrease the number of neutrons escaping from the fuel. Provision is made for heat removal, control elements, and monitoring instrumentation.

1. Single-Pass Air-Cooled Reactor

During normal operation, single-pass air-cooled reactors put into the atmosphere significant quantities of argon-41 (activation of argon-40) and iodine-131 fission products. Particulate matter may undergo activation also. As an example, the Brookhaven Graphite Research Reactor (BGRR) puts out about 16,000 curies per day of argon-41.(2) This activity is introduced into the atmosphere by a 400-foot high stack and is diluted with ambient air. About 10 millicuries per day of iodine-131 is also released to the atmosphere.(3) Liquid wastes are representative of other installations and will be discussed later.

2. Single-Pass Water-Cooled Reactor

The single-pass water-cooled reactors in this country are the plutonium-production reactors at Hanford, Washington. Cooling water for the reactors is taken from the Columbia River, subjected to water treatment processes to remove suspended impurities, passed through the reactors, held for several hours for decay of short-lived radionuclides, and returned to the Columbia River. The activity in the effluent is produced mainly by neutron activation, but also by fissioning of the uranium in the coolant waters and by leakage of fission products from failing fuel element jackets.

The radionuclides which have been identified are given in Table 1.(4)

TABLE 1.--Relative Abundance of Reactor Effluent Radionuclides*

90% of Total Activity	8% of Total Activity	2% of Total Activity		
^{24}Na	^{32}P†	^{14}C	^{45}Ca	^{46}Sc
^{31}Si	^{65}Zn	^{47}Sc	^{54}Mn	^{59}Fe
^{51}Cr	^{69}Zn	^{60}Co	^{85}Sr	^{89}Sr
^{56}Mn	^{72}Ga	^{90}Sr	^{91}Y	^{99}Mo
^{64}Cu	^{90}Y	^{103}Ru	^{95}Zr	^{115}Cd
^{76}As	^{91}Sr	^{131}I	^{111}Ag	^{137}Cs
^{239}Np	^{92}Sr	^{140}Ba	^{132}I	^{140}La
	^{92}Y	^{142}Pr	^{141}La	^{141}Ce
	^{93}Y	^{144}Ce-^{144}Pr	^{143}Ce	^{143}Pr
	^{97}Nb	^{147}Nd	^{145}Pr	^{147}Pm
	^{133}I	^{151}Pm	^{149}Nd	^{149}Pm
	^{135}I	^{156}Sm	^{152}Eu	^{153}Sm
	^{239}U	^{160}Tb	^{156}Eu	^{157}Eu
		^{227}Ac	^{187}W	^{210}Po
			^{238}U	^{239}Pu

* Reference time, four hours after irradiation.

† Radionuclides are underlined when their gamma energy is less than 0.1 MeV and/or less than a 5% gamma abundance.

Due to the short time of exposure to the reactor's neutron flux, only those nuclides which will reach saturation rapidly (where the number of atoms of the nuclide being produced equals the number of atoms of the nuclide decaying) will contribute significantly to the observed activity. These nuclides have relatively short half-lives.

In addition to decay, some radionuclides will be preferentially deposited and therefore not carried downstream. Table 2 shows the relative abundances of various activities in the Hanford cooling water at several distances downstream.(8)

TABLE 2.--Annual Average Concentration (pCi/l) of Several Radionuclides in Columbia River Water - 1961

Radionuclide	7 Miles	40 Miles	260 Miles
Total Beta	56,000	11,000	520
^{64}Cu	15,000	2,200	ND*
^{56}Mn	13,000	ND	ND
^{51}Cr	9,800	5,700	2,100
^{24}Na	9,500	1,800	ND
^{239}Np	5,000	2,400	110
^{76}As	3,700	1,200	ND
RE + Y†	2,000	390	24
^{31}Si	1,000	ND	ND
^{72}Ga	840	150	ND
^{69m}Zn	790	130	ND
^{65}Zn	600	340	90
^{32}P	410	260	68
^{46}Sc	57	33	24
^{131}I	18	10	ND
^{89}Sr-^{90}Sr	7.0	5.0	2.7
^{90}Sr	0.5	0.4	0.4

* Not detected.

† Rare Earth plus the Y isotopes listed in Table 1.

3. Recirculating Water Cooled

The radioactivity of concern in a recirculating or closed-loop water reactor comes from activation of corrosion products, fission products leaking from defective fuel elements, or fission products resulting from fissioning of uranium contaminating the outside surfaces of the fuel elements. Under normal conditions the activity will be released from the demineralizer's ion-exchange resins, from primary coolant leakage, and from maintenance and decontamination operations.

Tritium may also be produced in large quantities as at Shippingport(6) where LiOH is added to the coolant water to raise the pH to 0.5 - 10.5. The higher pH reduces corrosion of the structurals and therefore reduces the amount of activation product formed, excepting tritium. About 50 curies of tritium were discharged to the river during the first year of operation.(7)

Actual operational experience with the nuclear powered naval ships and estimates for the N.S. Savannah indicate the following radionuclides may be present in appreciable quantities during normal operations.(8) The reactor coolant water will contain cobalt-60, iron-55, iron-59, tantalum-182, and chromium-51 as the important corrosion products. The coolant water will contain strontium-90, zirconium-95, ruthenium-106, cesium-137, niobium-95, and cerium-144 as important fission products.

The reactor coolant water of the U.S.S. Nautilus contains the following radionuclides in quantity:(9) cobalt-60, iron-59, chromium-51, tantalum-182, copper-64, iodine-131, strontium-90, cerium-144, cesium-137.

The spent demineralizer from the Nautilus contains:

Cobalt-60	10 curies
Cobalt-58	0.5 curies
Iron-59	0.5 curies
Chromium-51	0.3 curies
Manganese-54	0.2 curies
Hafnium-175	1.0 curies

The differences in radionuclide composition between coolant systems can be attributed to different component compositions. The spent demineralizer's principle activity will be from intermediate and long half-life nuclides as the short half-life nuclides will have decayed out.

The waste from a particular reactor may differ from that indicated in the examples to some extent. Since the materials suitable for construction of reactors are restricted, the examples should provide a good guide.

The operation of a water reactor will also produce amounts of volatile radionuclides. At Shippingport these gases are collected and stored for a period of about 2 months. Krypton-85 will account for most of the activity remaining. It is then released to the atmosphere by stack discharge and diluted.

B. Reactor Accidents

The makeup of a radionuclide release in an accident depends upon the type of accident and the fission product inventory of the reactor at the time of the accident. Figures 2 and 3(10) give the relative activities of a number of fission products with time. These are calculated and would be applicable to initial reactor startup, a criticality incident, or a nuclear detonation.

An operating reactor, however, will have reached an equilibrium with the short half-life nuclides and will have a larger portion of the activity as longer half-life products. The fission product inventory in the core of a 500 megawatt reactor after 180 days of operation has been calculated(11) for 24 hours after shutdown and is summarized in Table 3.

There are great differences in the diffusion rates of the radionuclides into the water from the fuel elements. The halogens (bromine and iodine), the inert gases (xenon and krypton), and the alkali metals (cesium and rubidium) have escape rate coefficients about thirteen hundred times as great as the alkaline earths (strontium and barium).(12, 13) One would expect to find these elements escaping into the environment preferentially in case of an accident.

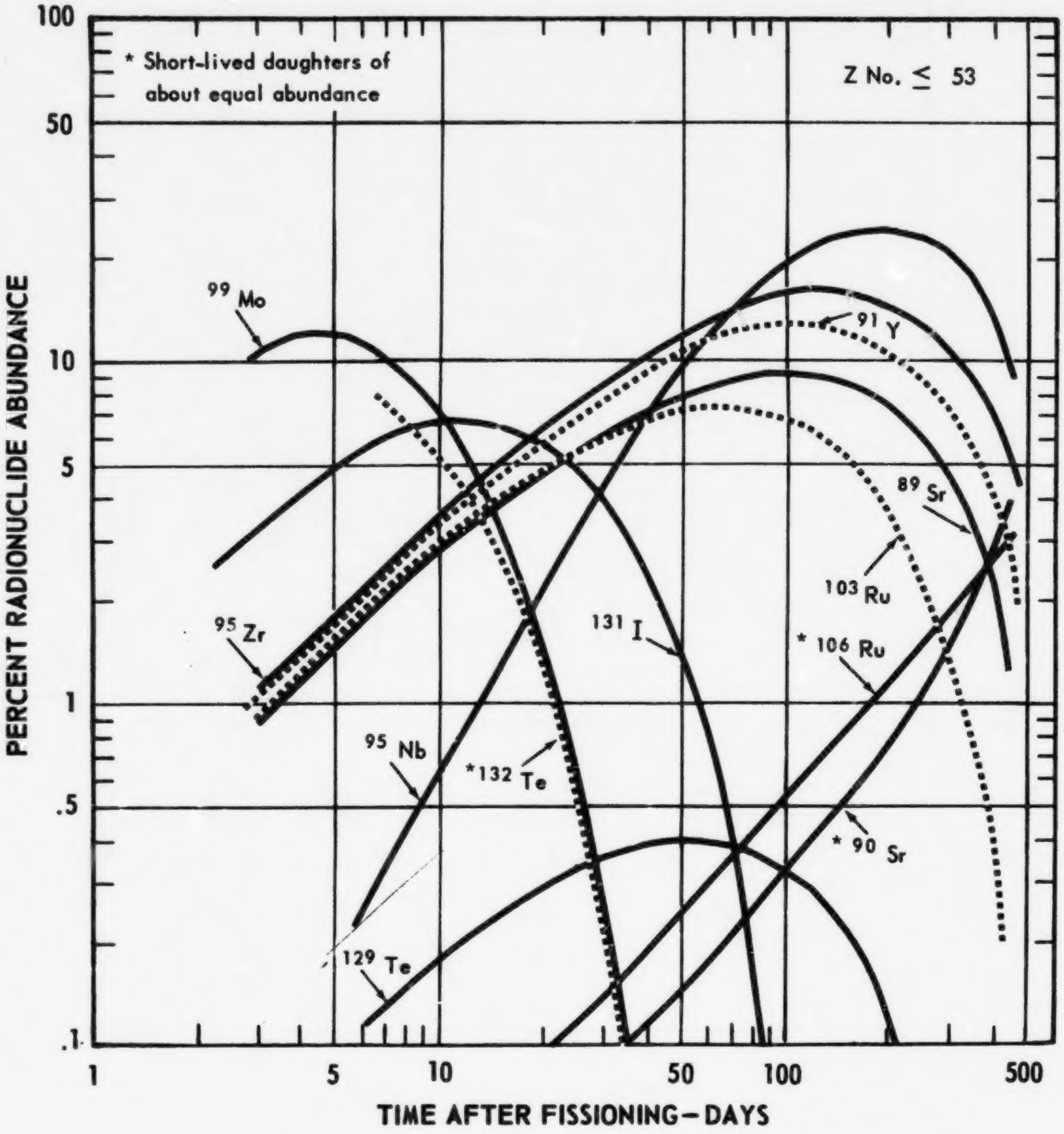

Figure 2.--Relative Abundances of Fission Product Nuclides

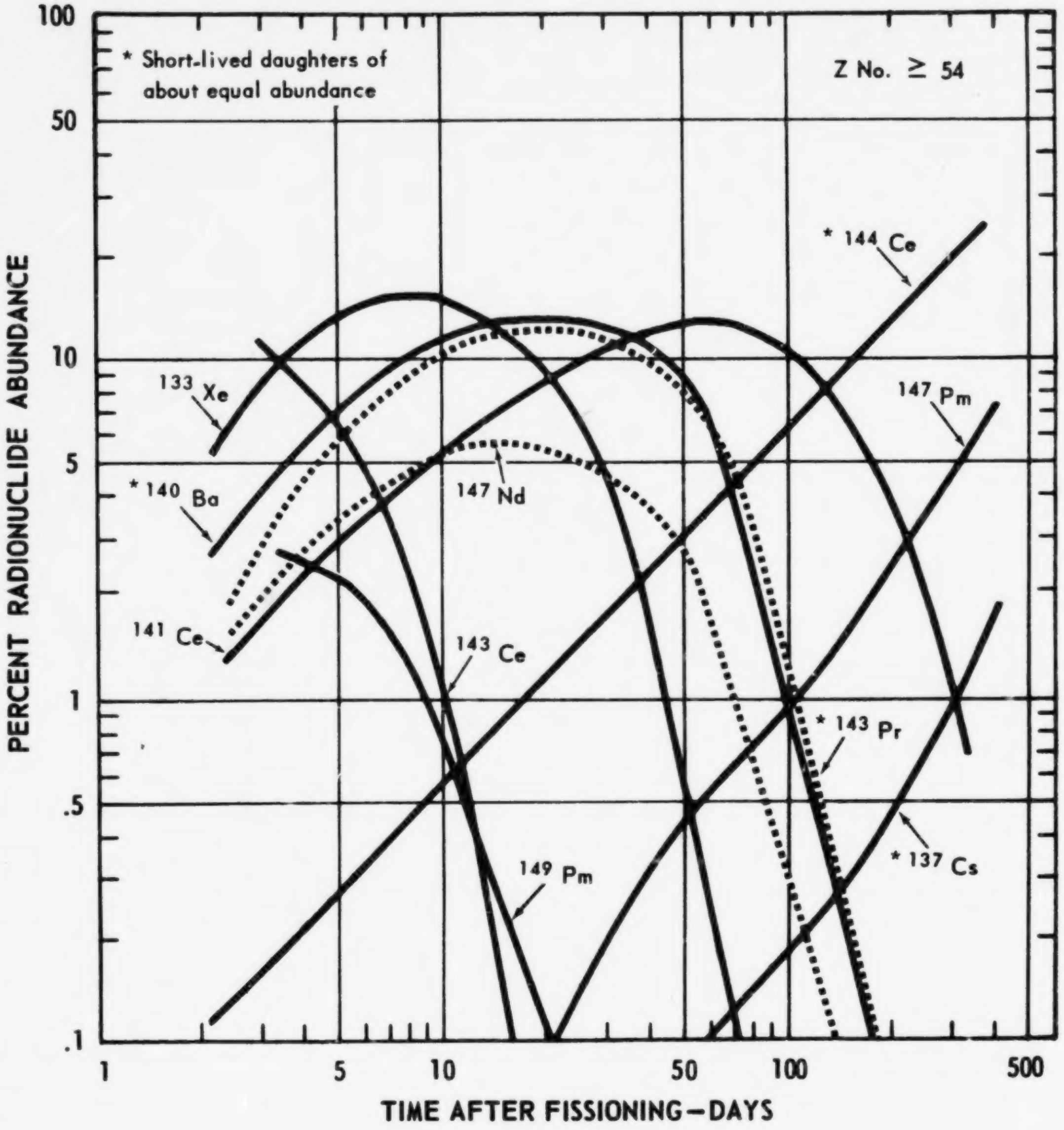

Figure 3.--Relative Abundances of Fission Product Nuclides

TABLE 3.--500 Mw Reactor Inventory After 180 Days of Operation

Activity	Curies
Total	4.1×10^8
Volatile	8.4×10^7
Iodine	5×10^7
Noble Gases	3.4×10^7
^{89}Sr	1.7×10^7
^{90}Sr	3×10^5
^{144}Ce	8×10^6

C. Fuel Reprocessing

The nature of the radionuclides in fuel to be reprocessed can be approximated by the core inventory after a period of operation as in Table 3. Most of the wastes are contained and do not reach the environment. However, some do, particularly the gaseous and volatile radionuclides. Table 4(14) gives the average emission rates of several radionuclides from the separations plant stacks at Hanford during 1961.

TABLE 4.--Average Hanford Stack Emissions - 1961

Radionuclide	Curies/day
^{131}I	0.7
^{95}Zr-^{95}Nb	0.005
^{103}Ru	0.003
^{106}Ru	0.005
^{141}Ce	0.006
^{144}Ce	<0.01

Earlier measurements at Hanford have indicated that the rare earth and yttrium activity released is about 0.02 curies per day, strontium-89 activity released is about 0.004 curies per day and strontium-90 activity is about 0.0005 curies per day.

Most of the activity released to the water at Hanford comes from the production reactors discussed earlier. Oak Ridge also does separations work and the measurable amounts of activity discharged to the Clinch River for the year 1961 is given in Table 5. (15)

TABLE 5.--Activity Discharged to Clinch River - 1961

Radionuclide	Curies/1961
Gross Beta	2230
^{106}Ru	2000
^{137}Cs	18
^{90}Sr	22
^{60}Co	31
^{131}I	3.7
^{95}Zr	20
^{95}Nb	70
^{144}Ce	4.2
RE - Ce*	24

* Total Rare Earth minus Ce.

Other radionuclides which have been identified in the Clinch River and/or below the Savannah River plant by a National Center for Radiological Health research study include cesium-134, chromium-51, iron-59, and natural potassium-40.

D. Ore Operations

The radionuclides from ore mining, milling, and processing operations are members of the uranium-238 and uranium-235 decay series. The most hazardous nuclide is radium-226.

E. Fallout

The nature of the radionuclides associated with fallout can be deduced from earlier discussions. The figures showing theoretical production (Figures 2 and 3) apply to fallout for the fission products formed. The nature of the induced activities in fallout will depend mainly on the site of detonation. An atmospheric burst produces quantities of carbon-14 and tritium. Bomb structurals and the type of terrain exposed in a surface burst will determine the nature of the other induced activities. Typical radionuclides formed include sodium-24, silicon-31, aluminum-28, chlorine-38, cobalt-60, zinc-65, manganese-54, and scandium-46. Special activities such as tungsten-185 may be introduced as tracers. The High Altitude Sampling Program(16) has resulted in identification of a large number of radionuclides in the upper atmosphere. Klement(17-19) and others have reviewed the potential radionuclides that may be produced in weapons detonations.

F. Medical Uses

Routine diagnostic and therapeutic applications of radionuclides are increasing in hospitals and medical research centers. Some radionuclides currently used internally(20-22) are listed in Table 6.

TABLE 6.--Common Medically-Used Radionuclides

$\underline{^{3}\mathrm{H}}$*	$\underline{^{14}\mathrm{C}}$	$^{22}\mathrm{Na}$	$^{24}\mathrm{Na}$
$\underline{^{32}\mathrm{P}}$	$\underline{^{35}\mathrm{S}}$	$^{42}\mathrm{K}$	$\underline{^{45}\mathrm{Ca}}$
$^{51}\mathrm{Cr}$	$^{54}\mathrm{Mn}$	$^{59}\mathrm{Fe}$	$^{60}\mathrm{Co}$
$^{64}\mathrm{Cu}$	$^{65}\mathrm{Zn}$	$^{74}\mathrm{As}$	$^{82}\mathrm{Br}$
$\underline{^{90}\mathrm{Y}}$	$^{124}\mathrm{Sb}$	$^{131}\mathrm{I}$	$^{198}\mathrm{Au}$

*Radionuclides which are not underlined are not gamma emitters.

A number of radionuclides are used in sealed source form. Some common gamma emitters are radium-226, radon-222, cobalt-60, cesium-137, iridium-192, europium-152-154, ruthenium-106, and cerium-144. Some non-gamma emitters include strontium-90, yttrium-90, and phosphorus-32.

The common method of disposal of low levels of these nuclides in solution is by discharge to the sewerage system.

G. Natural

A great number of naturally occurring radionuclides may be present. The heavy element radioactive families(23) decaying from uranium-238, uranium-235, and thorium-232 provide much of the natural radioactivity. Other common naturally occurring radionuclides include tritium, carbon-14, and potassium-40.

IV. VECTOR CONTAMINATION

A. Air

The naturally occurring radionuclides in air generally include radon and thoron and their daughters.

Induced activity in air is contributed mainly by neutron activation to form carbon-14, tritium, and argon-41.

The fission products that can occur in air are limited only by the source of contamination, planned or accidental release into the air, and age after injection. Identification and evaluation efforts can be aided by use of the above information in a process of elimination.

Radionuclides analyzed by surveillance networks include strontium-89, strontium-90, zirconium-95, cesium-137, barium-140, yttrium-91, cerium-141, cerium-144, promethium-147, and lead-210. Krypton-85 and iodine-131 are routinely released by operating reactors.

B. Fresh Water

The predominant naturally occurring radionuclides in water include uranium-238, radium-226, thorium-232, potassium-40, carbon-14, and tritium.

Neutron activation products and fission products from reactor and fuel reprocessing operations have been discussed.

C. Sea Water

The naturally occurring radionuclides in sea water should approximate those in fresh water. The use of nuclear-powered ships and the use of the ocean bottom as a low-level disposal area will contribute neutron activation and fission products to the sea in addition to those of fallout from weapons testing.

The physical state of fission product elements after vaporization and injection into sea water has been studied by Greendale and Ballou.(24) Their data is given in Table 7.

TABLE 7.--Probable Physical States of Elements in Sea Water

Element	Ionic	Colloidal	Particulate
Strontium	87	3	10
Yttrium	0	4	96
Zirconium	1	3	96
Niobium	0	0	100
Molybdenum	30	10	60
Ruthenium	0	5	95
Antimony	73	15	12
Tellurium	45	43	12
Iodine	90	8	2
Cerium	2	4	94

D. Stream and Marine Biota

Radionuclide uptake by fish in the Columbia River has been studied extensively at Hanford. The surveillance program routinely analyzes fish for total beta, phosphorus-32, zinc-65, scandium-46, arsenic-76, chromium-51, and neptunium-239.

Phosphorus-32, chromium-51, zinc-65, and neptunium-239 reached the Pacific Ocean in quantity. Oysters are routinely analyzed for scandium-46, potassium-40, zinc-65, zirconium-95, niobium-95, cesium-137, ruthenium-103, ruthenium-106, iodine-131, chromium-51, cerium-141, cerium-144, and phosphorus-32. Concentrations of zinc-65 (25) were found which are in agreement with other studies.(26, 27) Other radionuclides which can concentrate in marine biota include cobalt-60 and iron-59 in body tissue, and cesium-137 in muscle. The experience in the Marshall Islands has provided considerable practical uptake data.(28) A number of radionuclides have been identified in fish as a result of nuclear testing.(29) These include manganese-54, iron-55, iron-59, cobalt-57, cobalt-58, cobalt-60, zinc-65, strontium-90, yttrium-90, cadmium-113m, cadmium-115m, cesium-137, barium-140, lanthanum-140, cerium-144, and promethium-144.

E. Milk

The predominant radionuclides(30) biologically and quantitatively in milk are potassium-40, iodine-131, barium-140, lanthanum-140, cesium-137, and strontium-90. Other radionuclides which may be present include radium-226, zinc-65, phosphorus-32, strontium-89, cobalt-60, iron-55, iron-59, tellurium-132, and carbon-14.

F. Meat

For radionuclides to appear in meat, they must be absorbed from the gastrointestinal tract of the animal. Radionuclides which are not absorbed include zirconium-95, niobium-95, cerium-141, promethium-147, other rare earths, and plutonium.(31) Iodine is taken up by the thyroid. It has been identified in ground beef.

Some radionuclides which are partly absorbed include iron-55, iron-59, cobalt-60, zinc-65, tellurium-132, and barium-140. Cesium is efficiently absorbed and would be present in the meat. Strontium is absorbed also but is a bone-seeker. Phosphorus-32 has been detected in ducks around Hanford.(32)

G. Vegetation

Although foliar deposition of any radionuclide could occur, the Hanford surveillance program routinely analyzes native grasses for barium-140, lanthanum-140, zirconium-95, niobium-95, ruthenium-103, ruthenium-106, iodine-131, cerium-141, and cerium-144. Pine trees around the waste pits at Oak Ridge have been sampled.(33) The identified radionuclides come from fallout, blowoff from the waste pits or seepage from the pits. They are ruthenium-106, zirconium-95, niobium-95, cesium-137, and cerium-144. Irrigated alfalfa around Hanford has been analyzed (34) and scandium-46, potassium-40, zinc-65, zirconium-95, niobium-95, cesium-137, ruthenium-103, ruthenium-106, iodine-131, chromium-51, phosphorus-32, strontium-89, and strontium-90 have been identified.

In analyzing for various types of vegetables around Hanford, only potassium-40 and strontium-90 appeared regularly. Zinc-65 and phosphorus-32 were each identified once in six samples. Other radionuclides for which analysis in alfalfa was made were not identified.(35)

H. Soil

Since all fallout components will at least in part be deposited on the soil, characterization of soil samples is difficult. The general criteria for source, time, and nature of release apply. Cesium-137 is held in the soil rather tightly in comparison to strontium-90. The residual soil contamination in the Marshall Islands two years after weapons testing is shown in Table 8.(36)

TABLE 8.--Soil Nuclide Composition

Depth 0-1 inch

Nuclide	Percentage of Total
Cesium-137	<1%
Strontium-90	5
Ruthenium-106	10
Total Rare Earths	84

Induced activities which are possible in soils have been determined by a number of investigators.(17, 18, 37) The more common include sodium-24, phosphorus-32, potassium-42, calcium-45, iron-55, iron-59, and manganese-56.

V. SUMMARY

The nature of contamination of an environmental sample must be known for efficient quantitative gamma spectral analysis of the sample. Any knowledge of the source of contamination, nature of release, and time since the contamination will be helpful since these factors will modify the expected contamination. A knowledge of the food chain discrimination and other environmental factors will help eliminate unlikely or impossible radionuclides from consideration in qualitative and quantitative gamma spectroscopy.

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This material was prepared by Mr. W. D. Kelley of the Training and Manpower Development Program, National Center for Radiological Health.

INTRODUCTION TO STATISTICAL PRINCIPLES

J. W. Mullins*

I INTRODUCTION

Much of statistics is intuitive in nature even though of mathematical origin. Thus, it is possible to present the introductory principles in two ways, first, through mathematical derivations, second, through definitions with a minimum of mathematical manipulation. The second approach is used in this paper with application of principles as the primary objective.

II BASIC CONCEPTS

Basic statistical terminology is sometimes confusing because certain terms have different meanings to statisticians than to other scientists.

A Population and Sample(1)

Any group of individuals (or objects) having some common observable characteristic constitutes a population or universe. Any subgroup of a population is a statistical sample of that population. It should be noted that this statistical sample is made up of a number of individual items. The individual items could be samples of milk, etc. Throughout this discussion we will only be concerned with statistical samples. Populations can be finite (the number of dogs in a city, the number of cows in a milk shed, the number of assembly line parts manufactured per day, etc.) or infinite (e.g., all points on a line). In many cases a population or universe may be finite, but so large that we treat it as though it were infinite. The term population may refer either to the individuals or [illegible] to the measurements [illegible]

[illegible] distribution of sample [illegible] this distribution is [illegible] distribution of population [illegible] statistics

is to decide what information about the population distribution can be inferred from a study of the sample.

B Parameters and Statistics

Parameters are true, characteristic values of the population, such as the true mean, μ, and the true standard deviation, σ. In practical situations, parameters are not known and must be estimated from the data available or established by hypothesis. A statistic, therefore, is a characteristic value obtained from a sample and is an estimate of the true population parameter. The sample mean will normally be represented as $\overline{X}$ and the sample standard deviation as s.

In most experimental situations, populations are best represented by random samples. Random samples are those so selected that each individual in the population has an equal chance of being included in the sample. If some individuals in the universe are more likely to be chosen than others, the sample is said to be biased.

C Precision and Accuracy

Numbers can be precise, but not necessarily accurate. Precision refers to the reproducibility of the observations, i.e., how well the results agree within themselves. Accuracy refers to the correctness of a measurement or how closely the observation agrees with the true result.

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III. DISTRIBUTIONS

There are a number of distributions in statistics which can be expressed mathematically and/or graphically but before these [illegible], it is necessary to define several [illegible] which are descriptive of these distributions.

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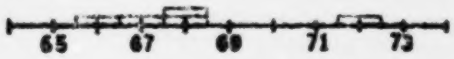
*R[illegible] Health [illegible] Section [illegible] Branch, Division of R[illegible] Health

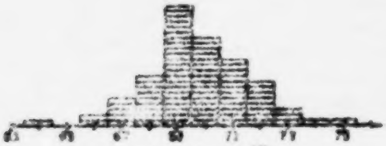
A Histograms

A histogram is a picture of a number of observations which illustrates the terms frequency and distribution. If the heights of 5 boys in a certain school are measured and recorded to the nearest inch, the numbers 68, 72, 66, 67, 68 can be represented by giving each measurement an equal unit of area above a scale marked with the heights. Such a representation is a histogram. (Figure 1)



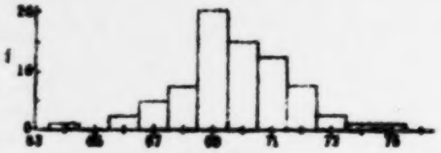
HEIGHT IN INCHES(1)
FIGURE 1

If another 75 boys are measured, a histogram is obtained from which at sight an idea can be formed of how the heights are distributed. (Figure 2)



HEIGHT IN INCHES(1)
FIGURE 2

Ordinarily, a histogram will be drawn without the lines showing the individual measurements, but the frequencies may be shown on a vertical scale to the left as in Figure 3. (f = frequency). The term frequency refers to the number of occurrences for each characteristic value interval.



HEIGHT IN INCHES(1)
FIGURE 3

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These measurements could be grouped into any length interval, i.e., instead of the nearest inch, we could measure to the nearest half inch and have twice as many intervals. As more and more measurements are made, the histogram approaches more and more closely the distribution of the heights of all the boys in the school. If more and more observations are made, and the intervals are made smaller and smaller in width, it is possible to imagine that the histogram would finally approach a smooth curve as in Figure 4. The total area under the smooth continuous curve is equal to the number of observations.

Another graphical description of the frequency with which each measurement occurs is given by a frequency polygon or frequency distribution. This is constructed by drawing line segments joining mid-points at the top of each column in the histogram. These frequency distributions can be drawn with decimal fractions of the total in place of actual frequencies. (Figure 5)

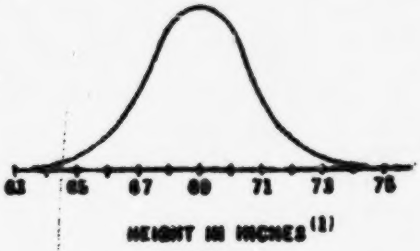


FIGURE 4

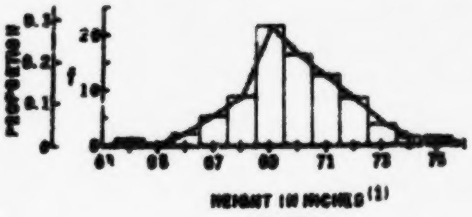
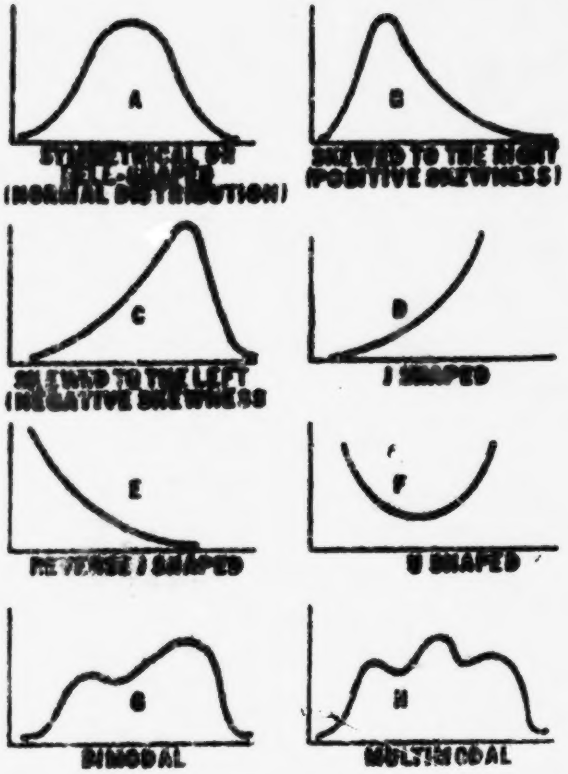


FIGURE 5



FREQUENCY DISTRIBUTIONS OF VARIOUS SHAPES(6)

FIGURE 6

Frequency distributions (frequency polygons) may produce a variety of curves, a number of which are reproduced in Figure 6. Many distributions of interest, i.e., those whose measurements are from chance causes only, will fall in category A, the normal distribution. The other curves are the result of some assignable cause producing a non-normal distribution.

B. Measures of Central Value and Dispersion

[illegible] Central Value

[illegible] refers to the location of the [illegible] the distribution. A useful [illegible] of the [illegible] of a distribution is the arithmetic mean or average. The population mean is defined as the sum of all the population observations divided by the total number of possible observations. The mean is usually represented as μ, each measurement as X_i, the total number of measurements as n, and the symbol for summation, or the sum of, is Σ. Equation (1) is then the symbolic form of the calculation of a population mean.

$$\mu = \frac{\sum_{i=1}^{n} X_i}{n} \qquad (1)$$

The sample mean, $\bar{X}$, is defined as the sum of the sample measurements divided by the number of measurements in the sample, n, as shown in equation (2)

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$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \qquad (2)$$

For the example of measuring the height of boys in a school, the mean for the five measurements would be:

$$\bar{X} = \frac{66 + 67 + 68 + 68 + 72}{5} = \frac{341}{5}$$

$$= 68.2 \text{ inches}$$

For example of 80 measurements, the mean would be:

$$\bar{X} = \frac{5,577}{80} = 69.7 \text{ inches}$$

Other measures of central value are the mode and the median. The mode is the value which occurs most frequently. In a histogram it is the midpoint of the interval with the greatest frequency, e.g., 69 inches in Figures 2 and 3. The median is the point on the scale of observations which has an equal area under the histogram on each side. The median is the middle observation of the ranked data if there are an odd number of cases and is the mean of the two central ranked observations if there are an even number of cases. In Figures 2 and 3, the median is 70 or 70 plus a very small fraction.

2 Dispersion

An important concept in statistics is that an average does not in itself give a clear picture of a distribution. It is quite possible for several distributions to give the same mean and yet have entirely different shapes. For example consider the following distributions of 10 numbers.
(f = frequency)

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Case 1

f	X
2	10
2	12
2	14
2	16
2	18

$\bar{X} = \frac{140}{10} = 14$

Case 2

f	X
5	10
5	18

$\bar{X} = \frac{140}{10} = 14$

Case 3

f	X
3	10
2	12
2	16
3	18

$\bar{X} = \frac{140}{10} = 14$

Case 4

f	X
1	10
2	12
4	14
2	16
1	18

$\bar{X} = \frac{140}{10} = 14$

Case 5

f	X
2	10
4	12
4	18

$\bar{X} = \frac{140}{10} = 14$

Case 6

f	X
1	10
1	14
6	16
2	18

$\bar{X} = \frac{140}{10} = 14$

It is desirable, therefore, to have a measure which indicates how the observations are spread from the average. This value could be called a measure of dispersion, spread or variability. At first glance, the sum of the deviations of the observations from the mean, equation (3) may seem to be a good

$$\sum_{i=1}^{n} (X_i - \bar{X}) \qquad (3)$$

measure for this purpose, but on further examination its value is seen to be always equal to zero.

Perhaps a better idea would be to take the absolute value of each deviation and then average the absolute values. We thereby obtain the mean deviation as in equation (4).

$$\frac{\Sigma \left| X_i - \bar{X} \right|}{N} = \text{average deviation} \qquad (4)$$

Actually the term mean or average deviation is a misnomer because it is not an average deviation, but the average of the absolute values of the deviations.

The problems encountered with the sums of arithmetic and absolute deviations can be circumvented by squaring the deviations before they are added, and then summing. We then obtain a value called the variance. The population variance, σ^2, is defined as the sum of the squares of the deviations of the observations from the true mean, μ, divided by the total number of possible observations in the population, n. Equation (5) is the symbolic form of the calculation of population variance.

$$\sigma^2 = \frac{(X_1-\mu)^2 + (X_2-\mu)^2 + \ldots + (X_n-\mu)^2}{n}$$

$$= \frac{\sum_{i=1}^{n} (X_i-\mu)^2}{n} \qquad (5)$$

The sample estimate of population variance is calculated slightly differently because sample variance will tend to be less than population variance, i.e., the spread or range (difference between highest and lowest observation) is less for a sample than for a population. The sample estimate of population variance, s^2, is defined as the sum of the squares of the deviations of the observations from the sample mean, $\overline{X}$, divided by one less than the number of observations in the sample, n-1. This is represented symbolically in equation (6).

$$s^2 = \frac{(X_1-\overline{X})^2 + (X_2-\overline{X})^2 + \ldots (X_n-\overline{X})}{n-1}$$

$$= \frac{\sum_{i=1}^{n} (X_i-\overline{X})^2}{n-1} \qquad (6)$$

Although variance is an expression of variability among all members of a [illegible] extremely useful in [illegible] computations, it does not [illegible] visualization of variation in terms of the original values dealt with. This is accomplished by means of the standard deviation which is calculated as the square root of the variance. The population standard deviation, σ, and the sample estimate of population standard deviation, s, are calculated as in equations (7) and (8).

$$\sigma = \sqrt{\sigma^2} = \sqrt{\frac{\sum_{i=1}^{n} (X_i-\mu)^2}{n}} \qquad (7)$$

$$s = \sqrt{s^2} = \sqrt{\frac{\sum_{i=1}^{n} (X_i-\overline{X})^2}{n-1}} \qquad (8)$$

Let us now consider the original 6 cases of 10 observations with a mean of 14.

Case 1

f*	X	$X-\overline{X}$	$(X-\overline{X})^2$
2	10	-4	2 × 16 = 32
2	12	-2	2 × 4 = 8
2	14	0	2 × 0 = 0
2	16	+2	2 × 4 = 8
2	18	+4	2 × 16 = 32
$\overline{X}$ = 14		= 0	80

$$s = \sqrt{s^2} = \sqrt{\frac{80}{9}} = 3.0$$

* f = frequency of occurrence

Case 2

f	X	$X-\overline{X}$	$(X-\overline{X})^2$
5	10	-4	5 × 16 = 80
5	18	+4	5 × 16 = 80
			= 160

$$s = \sqrt{\frac{160}{9}} = 4.2$$

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Case 3

f	X	X-$\overline{X}$	$(X-\overline{X})^2$
3	10	-4	16 × 3 = 48
2	12	-2	4 × 2 = 8
2	16	+2	4 × 2 = 8
3	18	+4	16 × 3 = 48
			112

$$s = \sqrt{\frac{112}{9}} = 3.5$$

Case 4

f	X	X-$\overline{X}$	$(X-\overline{X})^2$
1	10	-4	1 × 16 = 16
2	12	-2	2 × 4 = 8
4	14	0	4 × 0 = 0
2	16	+2	2 × 4 = 8
1	18	+4	1 × 16 = 16
			40

$$s = \sqrt{\frac{40}{9}} = 2.1$$

Case 5

f	X	X-$\overline{X}$	$(X-\overline{X})^2$
2	10	-4	2 × 16 = 32
4	12	-2	4 × 2 = 8
3			
4			
4	18	+4	4 × 16 = 64
			104

$$s = \sqrt{\frac{104}{9}} = 3.4$$

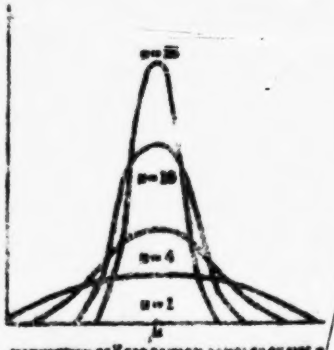
Case 6

f	X	X-$\overline{X}$	$(X-\overline{X})^2$
1	10	-4	1 × 16 = 16
1	14	0	1 × 0 = 0
5	16	+2	5 × 4 = 20
2	18	+4	2 × 16 = 32
			68

$$s = \sqrt{\frac{68}{9}} = 2.7$$

Thus, it appears that case 4 has the [illegible] variation from the mean, [illegible] 14 ± 2.1

[illegible] how is s related [illegible] is unlikely that $\overline{X}$ will vary from μ as much as s if the number of observations is large. The more measurements taken, the more reliable is the mean, $\overline{X}$, as an estimate of the true mean, μ. Figure 7 illustrates the distribution of sample means, $\overline{X}$'s, for various size samples from the same population. The curve for n = 1 (sample size of one observation) is the distribution for individuals in the population. All of the curves are centered at μ, but the scatter becomes less as n gets larger and when n becomes infinitely large or all values of the population are measured, then $\overline{X}$ and μ become equal. From a sample containing n measurements, we can calculate a mean $\overline{X}$ and a standard deviation s. Now, suppose another set of n measurements is taken and the mean and standard deviation of this set is calculated. This mean will not in general be exactly equal to the mean of the first set, although one expects that the difference of the means on the average will be considerably smaller than the difference between the individual measurements. The values of the standard deviation will be somewhat different also.



DISTRIBUTION OF $\overline{X}$ FOR RANDOM SAMPLES OF SIZE n FROM A NORMAL POPULATION WITH MEAN μ.

FIGURE 7[7]

Continue this process until many statistical samples have been taken, each with its own $\overline{X}$ and s. One might now ask: What is the standard deviation of the means? This standard deviation provides an indication of the reliability of any one of the means, $\overline{X}$, as an estimate of μ.

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Although it is difficult to show intuitively, it can be shown that the standard deviation of the means is equal to the standard deviation of the population mean, μ, divided by the square root of the number of individuals in any one statistical sample (see equation 9). As s is our best estimate

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}} \qquad (9)$$

of σ we may estimate $\sigma_{\bar{X}}$ with $s_{\bar{X}}$ which is calculated by equation 10.

$$s_{\bar{X}} = \frac{s}{\sqrt{n}} \qquad (10)$$

The estimated standard deviation of the mean is always less than that of individuals in the population but the increase in precision (decrease in variation) is not directly proportional to the size of the samples considered but, rather, to the square root of the sample size. Thus, if a certain standard deviation of the mean were obtained using samples of four individuals, it would be necessary to use samples of 16 individuals to decrease this standard deviation of the mean by one-half. Uncertainty (variability) can be decreased by using larger and larger samples, but efficiency in terms of cost and effort goes down rapidly.

C Propagation of Errors

Often it is necessary to add or subtract sets of numbers for which the errors are known or have been calculated. This is quite common in nuclear counting statistics. Very little need be said about this except to present the formula for combining errors in addition or subtraction. This formula for propagation of errors states that when adding or subtracting errors, the combined error [illegible] to the square root of the sum [illegible] the individual errors.

$$s_T = \sqrt{s_1^2 + s_2^2 + s_3^2 + \ldots. + s_m^2} \qquad (11)$$

(The propagation of errors law application is possible because variance is an additive property, i.e.,

$$\sigma_T^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots. + \sigma_m^2 \qquad (12)$$

$$\sigma_T = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots. + \sigma_m^2} \qquad (13)$$

and since s is the best estimate of σ, it is used to calculate sample errors when population data is not available.)

D The Normal Distribution(1)

In any series of measurements or observations, whether obtained as repeated determinations on the same individual or as independent determinations on similar individuals, the successive values will not be identical. The majority of such values may be in close agreement and usually will tend to cluster about some central value (such as the mean), but a definite degree of variation will be exhibited. When a large series of values are portrayed graphically by plotting frequency of occurrence against magnitude of measurement, the resultant distribution curve will take a characteristic shape or form.

There are three distributions of primary interest to us, the Normal or Gaussian Distribution, the Binomial Distribution and the Poisson Distribution.

The Normal Distribution is probably the most frequently encountered, or at least the one which is assumed to describe the majority of classes of physical measurements.

The Normal or Gaussian Distribution is characterized by the so-called "bell shaped curve." (Figure 8)

A normal curve is symmetric about the true mean, μ, of a population and it extends without limit to the left and right and approaches the abscissa asymptotically. The true mean locates the center of the

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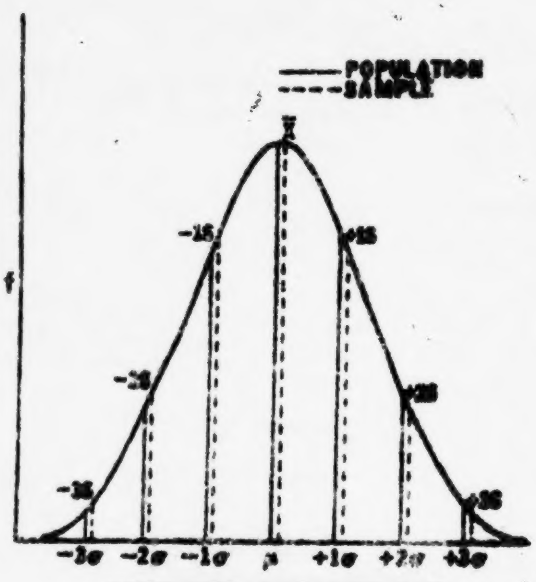

FIGURE 8

curve with reference to the abscissa. Also, it should be noted that the mean, median, and mode are all the same in a normal distribution of a population. In measuring means of samples, $\overline{X}$, we note deviations from the true mean, μ, but if the random sample is large enough, theoretically, a normal distribution should be obtained.

The standard deviation is one of the most useful measures of variation available as it is expressed in the same units of measure as are the original values. When applied to the proper type of data, e.g., a normal distribution of a population, it permits delineation of a zone or range within which a given portion of the individuals will lie. Thus, 68% of the individuals will have a value within the limits, the mean plus or minus one standard deviation, 95% will be within the limits of the mean plus or minus two [illegible] and 99.7% will be [illegible] plus or minus [illegible] deviations.

The limits or Confidence Levels for a population are noted below:

Population	Confidence Level or area under curve
$\mu \pm 1\,\sigma$	68%
$\mu \pm 2\,\sigma$	95%
$\mu \pm 3\,\sigma$	99.7%

The equation for the normal curve is

$$Y = \frac{1}{\sigma\sqrt{2\pi}} \quad e^{-1/2\left(\frac{X-\mu}{\sigma}\right)^2}$$

where Y = frequency, or height on ordinate corresponding to an assigned value of X

σ = population standard deviation

μ = population mean

X = magnitude of measurement on abscissa

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Another way of stating this equation is that the probability, dP, that a quantity X will lie between X and X + dX is:

$$dP = \frac{1}{\sigma\sqrt{2\pi}} e^{-1/2\left(\frac{X-\mu}{\sigma}\right)^2} dX \qquad (14)$$

A plot of $Y = \frac{dP}{dX}$ vs X produces the bell shaped curve.

These formulas are calculated on the basis of probabilities and are descriptive of the population, but not of great practical use.

A useful concept for relative frequency of observations is called the Cumulative Normal Distribution. The cumulative distribution function gives the relative frequency with which observations will fall below (to the left of) any specified value. This relative frequency is the area under the distribution curve from minus infinity to the specified value.

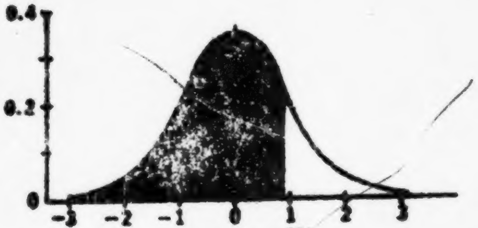

FIGURE 9$^{(1)}$

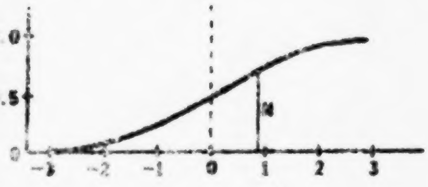

FIGURE 10$^{(1)}$

In the case of the normal distribution the areas under the curve from minus infinity to the point $\frac{X-\mu}{\sigma}$ have been tabulated. (Table 1) This table is entered with the value of z given by equation (15).

$$z = \frac{X-\mu}{\sigma} \qquad (15)$$

and the cumulated area is read from the area column. The height H indicated in Figure 10 is numerically equal to the area shaded under the normal curve in Figure 9 and thus gives the frequency with which observations less than or equal to any given value of X will occur.

This use of z factors enables us to calculate the proportion of cases which should fall between certain measures of X. For example: in a normal distribution $\mu = 30$, $\sigma = 5$. What proportion of cases fall between 20 and 35?

$$X = 20 \text{ gives } z = \frac{X-\mu}{\sigma} = \frac{20-30}{5} = -2.0$$

$$X = 35 \text{ gives } z = \frac{X-\mu}{\sigma} = \frac{35-30}{5} = 1.0$$

Table 1 gives the area to the left of -2.0 to be 0.0228 and the area to the left of 1.0 to be 0.8413. Thus the area (proportion of cases) between X = 20 and X = 35 is 0.8413 - 0.0228 = 0.8185 Thus 81.85% of all cases lie between 20 and 35. (Figure 11)

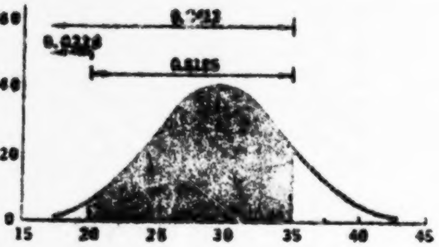

FIGURE 11$^{(1)}$

Table 1.(11) CUMULATIVE NORMAL DISTRIBUTION (cont.)

z	X	Area	z	X	Area
-3.25	μ - 3.25σ	.0006	-1.00	μ - 1.00σ	.1587
-3.20	μ - 3.20σ	.0007	- .95	μ - .95σ	.1711
-3.15	μ - 3.15σ	.0008	- .90	μ - .90σ	.1841
-3.10	μ - 3.10σ	.0010	- .85	μ - .85σ	.1977
-3.05	μ - 3.05σ	.0011	- .80	μ - .80σ	.2119
-3.00	μ - 3.00σ	.0013	- .75	μ - .75σ	.2266
-2.95	μ - 2.95σ	.0016	- .70	μ - .70σ	.2420
-2.90	μ - 2.90σ	.0019	- .65	μ - .65σ	.2578
-2.85	μ - 2.85σ	.0022	- .60	μ - .60σ	.2743
-2.80	μ - 2.80σ	.0026	- .55	μ - .55σ	.2912
-2.75	μ - 2.75σ	.0030	- .50	μ - .50σ	.3085
-2.70	μ - 2.70σ	.0035	- .45	μ - .45σ	.3264
-2.65	μ - 2.65σ	.0040	- .40	μ - .40σ	.3446
-2.60	μ - 2.60σ	.0047	- .35	μ - .35σ	.3632
-2.55	μ - 2.55σ	.0054	- .30	μ - .30σ	.3821
-2.50	μ - 2.50σ	.0062	- .25	μ - .25σ	.4013
-2.45	μ - 2.45σ	.0071	- .20	μ - .20σ	.4207
-2.40	μ - 2.40σ	.0082	- .15	μ - .15σ	.4404
-2.35	μ - 2.35σ	.0094	- .10	μ - .10σ	.4602
-2.30	μ - 2.30σ	.0107	- .05	μ - .05σ	.4801
-2.25	μ - 2.25σ	.0122			
-2.20	μ - 2.20σ	.0139			
-2.15	μ - 2.15σ	.0158	.00	μ	.5000
-2.10	μ - 2.10σ	.0179			
-2.05	μ - 2.05σ	.0202			
-2.00	μ - 2.00σ	.0228	.05	μ + .05σ	.5199
-1.95	μ - 1.95σ	.0256	.10	μ + .10σ	.5398
-1.90	μ - 1.90σ	.0287	.15	μ + .15σ	.5596
-1.85	μ - 1.85σ	.0322	.20	μ + .20σ	.5793
-1.80	μ - 1.80σ	.0359	.25	μ + .25σ	.5987
-1.75	μ - 1.75σ	.0401	.30	μ + .30σ	.6179
-1.70	μ - 1.70σ	.0446	.35	μ + .35σ	.6368
-1.65	μ - 1.65σ	.0495	.40	μ + .40σ	.6554
-1.60	μ - 1.60σ	.0548	.45	μ + .45σ	.6736
-1.55	μ - 1.55σ	.0606	.50	μ + .50σ	.6915
-1.50	μ - 1.50σ	.0668	.55	μ + .55σ	.7088
-1.45	μ - 1.45σ	.0735	.60	μ + .60σ	.7257
-1.40	μ - 1.40σ	.0808	.65	μ + .65σ	.7422
-1.35	μ - 1.35σ	.0885	.70	μ + .70σ	.7580
-1.30	μ - 1.30σ	.0968	.75	μ + .75σ	.7734
-1.25	μ - 1.25σ	.1056	.80	μ + .80σ	.7881
-1.20	[illegible]	[illegible]	.85	μ + .85σ	.8023
[illegible]	[illegible]	[illegible]	.90	μ + .90σ	.8159
-1.10	[illegible]	[illegible]	.95	μ + .95σ	.8289
-1.05	[illegible]	.1469	1.00	μ + 1.00σ	.8413

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Table 1.⁽¹⁾ CUMULATIVE NORMAL DISTRIBUTION (Cont.)

z	X	Area	z	X	Area
1.05	μ + 1.05σ	.8531	-4.265	μ - 4.265σ	.00001
1.10	μ + 1.10σ	.8643	-3.719	μ - 3.719σ	.0001
1.15	μ + 1.15σ	.8749	-3.090	μ - 3.090σ	.001
1.20	μ + 1.20σ	.8849	-2.576	μ - 2.576σ	.005
1.25	μ + 1.25σ	.8944	-2.326	μ - 2.326σ	.01
1.30	μ + 1.30σ	.9032	-2.054	μ - 2.054σ	.02
1.35	μ + 1.35σ	.9115	-1.960	μ - 1.960σ	.025
1.40	μ + 1.40σ	.9192	-1.881	μ - 1.881σ	.03
1.45	μ + 1.45σ	.9265	-1.751	μ - 1.751σ	.04
1.50	μ + 1.50σ	.9332	-1.645	μ - 1.645σ	.05
1.55	μ + 1.55σ	.9394	-1.555	μ - 1.555σ	.06
1.60	μ + 1.60σ	.9452	-1.476	μ - 1.476σ	.07
1.65	μ + 1.65σ	.9505	-1.405	μ - 1.405σ	.08
1.70	μ + 1.70σ	.9554	-1.341	μ - 1.341σ	.09
1.75	μ + 1.75σ	.9599	-1.282	μ - 1.282σ	.10
1.80	μ + 1.80σ	.9641	-1.036	μ - 1.035σ	.15
1.85	μ + 1.85σ	.9678	- .842	μ - .842σ	.20
1.90	μ + 1.90σ	.9713	- .674	μ - .674σ	.25
1.95	μ + 1.95σ	.9744	- .524	μ - .524σ	.30
2.00	μ + 2.00σ	.9772	- .385	μ - .385σ	.35
2.05	μ + 2.05σ	.9798	- .253	μ - .253σ	.40
2.10	μ + 2.10σ	.9821	- .126	μ - .126σ	.45
2.15	μ + 2.15σ	.9842	0	μ	.50
2.20	μ + 2.20σ	.9861	.126	μ + .126σ	.55
2.25	μ + 2.25σ	.9878	.253	μ + .253σ	.60
2.30	μ + 2.30σ	.9893	.385	μ + .385σ	.65
2.35	μ + 2.35σ	.9906	.524	μ + .524σ	.70
2.40	μ + 2.40σ	.9918	.674	μ + .674σ	.75
2.45	μ + 2.45σ	.9929	.842	μ + .842σ	.80
2.50	μ + 2.50σ	.9938	1.036	μ + 1.036σ	.85
2.55	μ + 2.55σ	.9946	1.282	μ + 1.282σ	.90
2.60	μ + 2.60σ	.9953	1.341	μ + 1.341σ	.91
2.65	μ + 2.65σ	.9960	1.405	μ + 1.405σ	.92
2.70	μ + 2.70σ	.9965	1.476	μ + 1.476σ	.93
2.75	μ + 2.75σ	.9970	1.555	μ + 1.555σ	.94
2.80	μ + 2.80σ	.9974	1.645	μ + 1.645σ	.95
2.85	μ + 2.85σ	.9978	1.751	μ + 1.751σ	.96
2.90	μ + 2.90σ	.9981	1.881	μ + 1.881σ	.97
2.95	μ + 2.95σ	.9984	1.960	μ + 1.960σ	.975
3.00	μ + 3.00σ	.9987	2.054	μ + 2.054σ	.98
3.05	μ + 3.05σ	.9889	2.326	μ + 2.326σ	.99
[illegible]	μ + 3.10σ	.9990	2.576	μ + 2.576σ	.995
[illegible]	+ 3.15σ	.9992	3.090	μ + 3.090σ	.999
3.20	3.20σ	.9993	3.719	μ + 3.719σ	.9999
3.25	+ 3.25σ	.9994	4.265	μ + 4.265σ	.99999

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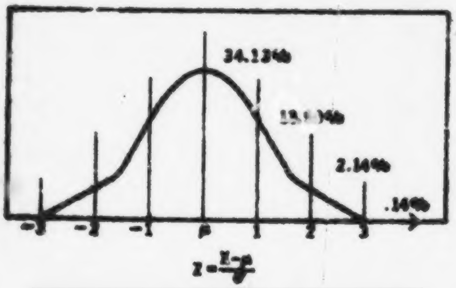
If the z numbers are expressed in terms of standard deviations, it can be proved that 34% of the area under the curve is encompassed from μ to + 1 σ, 13.59% from + 1 σ to + 2 σ, etc.

Since the z numbers are expressed in terms of standard deviations from the mean it can be shown that 34% of the area under the curve lies between μ and + 1 σ, etc. as in Figure 12.



PERCENTAGE OF THE POPULATION IN VARIOUS INTERVALS OF A NORMAL DISTRIBUTION

FIGURE 12(7)

Before going on to discuss the binomial and poisson distributions, it is probably advisable to study Table 2. This table summarizes the properties of the Normal Distribution as applied to sample and population.

Table 2. SOME PROPERTIES OF THE NORMAL DISTRIBUTION

	Sample statistic	Population parameter
Mean	$\overline{X}$	μ
Variance	s^2	σ^2
Standard deviation	s	σ

F. The Binomial Distribution(3)

The binomial distribution is the fundamental [illegible] distribution governing [illegible] other distributions [illegible] theoretically, it was the first probability distribution to be described theoretically.

For probability studies on processes such as flipping a coin or casting a die, the binomial distribution may be applied. This law is commonly applied to cases of occurrence or non-occurrence, i.e., response or non-response, death or survival, or the presence or absence of some characteristic in individuals in successive samples, and produces a distribution which is not normal.

If there is a constant probability of occurrence, p, and a probability of non-occurrence, q, where q = 1-p in samples of size k, the expected relative frequency of 0, 1, 2, 3, ... k occurrences in groups is given by the successive terms of the binomial expansion of

$$(q + p)^k \qquad (16)$$

The probability that the event will happen X times and will not happen Y times is

$$p(X) = \frac{n!}{X!\,Y!}\, p^X q^Y \qquad (17)$$

n = total no. of events.

The expected mean value of X (mean occurrence) is equal to np and the variance is given as npq. Thus the standard deviation from the expected mean is $\sqrt{npq}$. (See Table 3.)

In terms of proportions or percentages, the mean is equal to p, the variance is calculated as

$$\frac{pq}{n}$$

and the standard deviation as $\sqrt{\frac{pq}{n}}$.

When n is large, the binomial law may be approximated by an exponential expression which is essentially the same as the continuous normal distribution law. The normal law then becomes an approximation for the binomial law provided that n is large and p and q are about equal, so that $\sqrt{npq}$ is large compared with q-p. When n is

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large and p is very small, the binomial law reduces approximately to the Poisson Distribution.

Table 3. SOME PROPERTIES OF THE BINOMIAL DISTRIBUTION

	Population parameters
Mean	$\mu = np$
Variance	$\sigma^2 = npq$
Standard deviation	$\sigma = \sqrt{npq}$

F The Poisson Distribution(4)

The expression for the Poisson Distribution may be derived directly from probability considerations or indirectly as a limiting case of the binomial distribution. If for a specified change in some variable, e.g., a given interval of time, the probability p that an event will happen is very small and if the probability q that it will not happen approaches unity, then in a large number of trials n, the probability that the event will happen X times is

$$p(X) = \frac{e^{-\mu}\mu^X}{X!} \qquad (18)$$

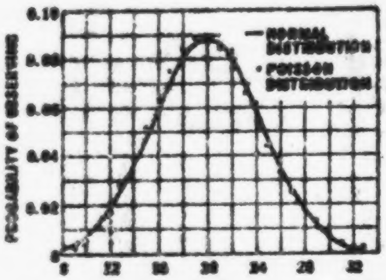
In this expression μ is the expected mean and is equal to np. (In practice μ is approximated by the arithmetical average of a set of measured values). The Poisson Distribution is discontinuous, i.e., μ and X are integers, which distinguishes it from the normal distribution where X is a continuous variable. If μ is a fairly large number, say 100 or larger, the Poisson Distribution is adequately approximated by a special normal distribution

$$dP = \frac{1}{\sqrt{2\pi\mu}} e^{-\frac{(X-\mu)^2}{2\mu}} dX \qquad (19)$$

[illegible] comparison with equation (14) [illegible] that the standard deviation is given [illegible]

$$\sigma = \sqrt{\mu} \qquad (20)$$

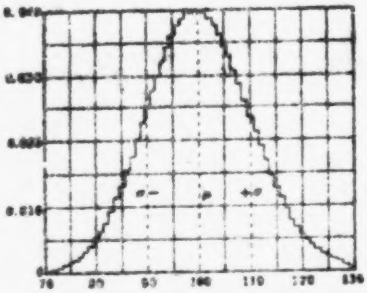
The standard deviation of a normal distribution approximating a Poisson Distribution is therefore specified when μ is specified; but in general the standard deviation of a normal distribution can have any value for any μ. In most applications equation (19) is an adequate representation of the Poisson Distribution. Even if μ is as low as 20, the approximation is fair (as in Figure 13).



THE NORMAL DISTRIBUTION AS AN APPROXIMATION TO THE POISSON DISTRIBUTION AT AN AVERAGE VALUE OF 20

FIGURE 13(9)

Actually, the Poisson Distribution must always be represented by a histogram, since X must assume whole-number values only. Figure 14 illustrates the Poisson Distribution for μ = 100; the slight asymmetries should be noted, as well as the similarity with the symmetric normal distribution.



POISSON DISTRIBUTION FOR μ = 100

FIGURE 14

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The Poisson Distribution is accepted as approximating the normal distributions for values of $\mu \geq 30$.

For small values of μ, say, between $\mu = 1$ and $\mu = 10$, the Poisson Distribution is very asymmetric and is not well approximated by the normal distribution.

It should be noted that the standard deviation of a Poisson Distribution is always equal to the square root of the mean as in equation (21). In nuclear counting statistics, the average number of events is large enough that the sample standard deviation and the population standard deviation are very nearly equal.

$$s = \sqrt{\overline{X}} \qquad (21)$$

Example: Calculate the standard deviation for a count rate of radioactive sample which produces a mean of 1000 counts.

$$s = \sqrt{\overline{X}} = \sqrt{1000} = 31.62 \text{ counts}$$

Table 4 summarizes the properties of the Poisson Distribution.

Table 4. SOME PROPERTIES OF THE POISSON DISTRIBUTION

	Sample statistics	Population parameters
Mean	$\overline{X}$	μ
Variance	$s^2 = \overline{X}$	$\sigma^2 = \mu$
Standard deviation	$s = \sqrt{\overline{X}}$	$\sigma = \sqrt{\mu}$

IV SUMMARY

There are three major statistical distributions of primary interest, the Binomial which is the fundamental one, the Poisson Distribution which is a special application of the Binomial, and the normal distribution. It is important to know the basic statistical terminology which applies to all distributions, but it is also necessary to know that the distributions are different. Hence, calculations of certain parameters such as standard deviation are performed differently on each distribution.

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Representative Sampling Techniques

I. INTRODUCTION

The environmental surveillance program uses sampling to achieve its ends. Representative sampling is needed for a reliable estimate of the population, and this estimate must also be precise to be useful.

A. Planning the Survey

A survey should be conceived, developed, carried out, and the results evaluated in a systematic manner. The application of appropriate statistical theory will aid the investigator in obtaining the most for his money.

In planning a survey, some basic criteria must be defined. These include: (1) the specific information desired, (2) relative importance of the specific information, and (3) what decisions will be made on the basis of the possible survey results. With this information one can at least get a feeling for the accuracy required of the survey. Before designing the actual sampling plan to be used the following parameters need to be defined: (1) the population to be surveyed; (2) the exact information desired for this population; and (3) the necessary precision and accuracy of results.

B. Designing the Survey

The criteria for a statistically designed survey would require that the survey:(1)

(1) be designed such that an objective measure of precision can be made;

(2) be simple enough to be practical and to be completed on schedule;

(3) be designed to yield maximum precision per unit cost; and

(4) be completed according to the directions given.

The characteristics of several types of sampling designs will be discussed. These characteristics help in choosing between various sampling designs. The material presented will not provide all the information needed to design, conduct, and evaluate a large-scale survey but should provide an introduction to the subject.

C. Sampling Error

Sampling error is the inability of the survey to reproduce the results obtained by a complete count or assay of the population using the same assay techniques. Sampling error does not include errors in measurement techniques or biases resulting from other nonsampling errors. Our ultimate aim is not just to know the sampling error or precision (which we measure with a statistically designed sampling plan) but to know the accuracy of the results. The survey should be designed to minimize the combined precision and bias errors.

II. SAMPLING PLANS

A. Judgment versus Random Sampling

The two types of samples that can be used in a survey are the judgment and the random (or probability) sample. The judgment sample relies upon the expertise of its user to be a representative sample. The random sample relies upon itself to establish limits of precision. The survey itself will determine which technique is more efficient.

There is a twofold problem with judgment sampling. Judgment samples are open to selection bias. The surveyor may not and probably will not select his sample (but most importantly cannot show) such that each possible sample of a given size has a known probability of selection. The surveyor then is in a position of not knowing what biases may be involved. The second part of the problem is the inability to estimate the sampling error since the standard equations are based on the assumption that the probability of an individual being included in a sample is known. The equations are also limited in use to the particular sample survey design for which they were developed.

Random or probability sampling allows objective measurement of sampling error. It also permits comparison of different types of surveys and selection of the most efficient design. In certain cases, particularly where small samples are involved, the judgment sample error, even with its possible bias, may be smaller than the sampling error of the random sample.

The choice between judgment and random sampling can be made by considering the problem as have Hansen, Hurwitz and Madow.(2) "A suggested answer to this question is the following: If it is important that reliable results be obtained, and if a fairly heavy loss may be involved if the wrong action or decision is taken as a consequence of having depended on results that actually turn out to have larger errors than are considered tolerable, then a method for which the risk of error can be controlled should be used if possible. On the other hand, if conditions are such that only fairly rough estimates are required from the sampling, and important decisions do not hinge on the result, then only a small sampling is required, and the price to be paid for using sampling whose accuracy can be measured may not be justified. Under these conditions it may be that the biases of a low-cost nonrandom method will be considerably less important than the random errors resulting from the small size of the sample, and thus such methods may be expected to produce results of sufficient reliability more economically than would more rigorous alternative methods. However, it appears reasonable to assume that, in most instances in which a fairly precise estimate is desired, and for which, therefore, a fairly large sampling is used, the possible biases of nonrandom methods may be sufficiently serious to make them less efficient in terms of precision of results per unit of cost than an appropriate probability sampling method."

It can be seen that the choice between a judgment or a probability (random) sample can be made on the basis of the objectives and requirements of the survey.

B. Simple Random Sampling

A probability or random sample is any sample in which the probabilities of selection are known.(3-5) Probability samples are selected by chance mechanisms. The chance mechanism may range from "marbles in a jar" to the use of a "table of random numbers." The choice is one of convenience as long as only chance mechanisms are used to make the sample selection. The chances of selection of any individual in the sample can be calculated by the laws of probability. The probability or random sample is also, by definition, free of selection bias. When chance mechanisms are used to select the sample, there can be no relationship between its selection and some characteristic of the sample. Unsuspected biases are eliminated.

Simple random sampling is a limiting case of random sampling. In simple random sampling, the chances of selection of every possible sample (for a given statistical sample size) must be the same. Each member of the population has an equal probability of being selected. Each possible simple random statistical sample of a given size has the same probability of selection as any other. The other forms of random sampling--stratification, cluster, systematic, etc.--can be considered as refinements whose purpose is to make the survey more efficient. The increase in efficiency may result from a smaller sampling error with the same number of sampling units in the statistical sample, from reducing the number of sampling units required to achieve a specified sampling error, or from reduced cost in the collection of the required number of sampling units by using techniques such as clustering.

Where we know little about the population to be sampled, simple random sampling or double sampling would be the choice. Where we have pertinent information about the population, we may be able to increase the efficiency of the statistical sample by stratification, clustering, or systematic sampling.

C. Stratification

Where some knowledge of the population being sampled is available, the elements may be divided into groups more homogeneous than the total population. This practice is routinely applied in dividing areas into subareas based upon agricultural practices, rainfall, type of soil, etc. After the population is divided into non-overlapping groups or "strata" (stratification), a random statistical sample can be taken from each stratum.(6-8) The random sampling of each stratum is done independently of the other strata. The statistical sample from all the strata is the stratified statistical sample.

In order to increase the efficiency of the statistical sample, the strata must be homogeneous with respect to the purpose of the survey. Stratification of a milk supply according to observed iodine-131 concentration gradients may not apply to a study of strontium-90. For iodine-131, foliar deposition is the important pathway, whereas root uptake may well be an important or even dominant pathway for strontium-90.

Where each stratum contributes the same number of units to the statistical sample, a proportionate stratified sample occurs. The proportionate stratified sample has a uniform sampling fraction. It is not necessary, though, to be confined to a uniform sampling fraction. When the sampling fraction differs among strata, the results must be weighted to avoid bias. A non-uniform sampling fraction is referred to as disproportionate stratified sampling.

The selection of sampling units within the strata must be randomly accomplished, most easily by simple random sampling.

The use of non-uniform or variable sampling fractions is useful in oversampling certain strata. Generally, the more variable strata are oversampled to make the whole statistical sample more efficient. In estimating the radioactivity content, a grand average of the strata averages would be biased. That is, the strata that are oversampled would overly influence the estimated population value. Weighting of strata values using the reciprocal of the sampling fraction will give an unbiased estimate.

A general rule has been established by Stuart(6) for achieving maximum precision from stratification. "As it happens, the rule is very simple: to maximize precision, the sampling fraction in each stratum should be proportional to the square root of the variance in that stratum." For example, should the variances of two strata have a ratio of 9 to 1, the sampling fractions should have a ratio of 3 to 1.

The problem of dividing an area or population into strata has also been solved by Stuart.(6) "The effect of the gain in precision from stratified sampling with uniform sampling fraction depends on the variation between stratum averages. The greater the variation between the stratum averages, the greater the gain in precision."

The advantage of stratification is the increased precision that is attainable. Although cost of obtaining the statistical sample can be used as a criterion in modifying the stratification process, cluster sampling lead is generally used to reduce costs.

D. Cluster Sampling

Cluster sampling, in contrast to stratified sampling, usually causes greater error (for a given statistical sample size) than simple random sampling.(9-11) Justification for this increase in sampling error, or a larger statistical sample size to maintain a certain error, comes from the reduced cost of the sample survey. The result is a decrease in sampling error per unit cost.

In cluster sampling the population is divided into groups as in stratification, but the selection process is different. Each stratum must be sampled to avoid bias, but only one or certain clusters are sampled. The selection of which cluster or clusters to sample is done by simple random sampling. These clusters may be dairies in a milkshed, farms in a county, counties in a State or whatever can be conveniently defined and listed.

The two simplest types of cluster sampling are: (1) simple one-stage sampling; and (2) simple two-stage sampling. In simple one-stage sampling, simple random sampling is used to select the clusters to be sampled. All sampling units in the selected clusters make up the sample. In simple two-stage sampling, the clusters or primary units are selected by simple random sampling. In the second-stage sampling, the sampling units in the population are chosen from the selected clusters by simple random sampling. To simplify two-stage sampling, each cluster will contribute the same number of sampling units to the sample; that is, there will be a uniform sampling fraction.

In practice, the clusters will not have the same number of sampling units in each cluster, so some weighting procedure must be used to avoid a biased representation of the population. The weighting factor should be proportional to the size of the cluster.

The nature of cluster sampling dictates the qualities of an ideal cluster. In the extreme situation, one cluster might be selected to represent the population. Obviously the cluster should be as variable as the population. This is in direct contrast to stratification, where ideally all variability is removed from within the strata and is manifested as differing strata averages. If a county were selected to represent a state, it should be as variable in the characteristic under study as the State. The inevitable conclusion is that good stratification is poor clustering and vice versa.

The choice between simple or stratified random sampling and cluster sampling has another complicating factor. If one had to sample the radioactivity content of wells in a State, a complete list of the wells would be required to do simple or stratified random sampling. The compilation of such a list may well be prohibitively expensive. The application of cluster sampling techniques to counties and townships in the selected counties would reduce the listing problem to manageable proportions. In many situations, a list of the population is impossible or unfeasible. Cluster sampling must be used at least initially.

E. Systematic Sampling

The final common form of random sampling to be discussed is systematic sampling.(12) An example of systematic sampling would be the taking of every n'th (e.g., 175th) bottle of milk coming from the bottling line. The selection of which of the 175 bottles to start with would be accomplished by simple random sampling. Systematic sampling resembles simple random sampling.

The danger of systematic sampling lies in possible periodicities in the population.

Where periodicities do occur, systematic sampling may completely miss this variability. Only where periodicities are known not to be present in the population can systematic sampling be safely used. Systematic sampling can be used advantageously where adjacent sampling units are very similar, with the similarity decreasing as time or distance increases. In such a situation, systematic sampling may be considerably more efficient than simple random sampling.

Systematic sampling is one of the common sampling techniques available for a random or probability sample. These techniques--simple random sampling, stratified random sampling, cluster sampling, and systematic sampling--are not completely separate designs to be used exclusive of one another. In most situations a combination of types will be involved. The methods of estimating population values are determined by the sampling designs used. A statistician's aid in setting up the more complicated program should yield dividends in economy in number of samples required and in the methods of estimating population values.

III. SELECTION OF A SAMPLING DESIGN

A. Objectives

If the objective requires that great reliance be placed on the data from the survey, random sampling is mandatory. If only a few samples will be taken, judgment sampling may be more representative of an area.

Simple random sampling is the basis for all probability or random techniques and serves as a reference point from which modifications to increase the efficiency are evaluated (more precise estimates with the same effort or a reduction in effort for a desired precision).

In large population surveys, a list of the members of the population being sampled (frame) may be prohibitively expensive or impossible to obtain. In these cases, cluster sampling provides an attractive alternate. The primary sampling units can be easily defined as geographical areas, such as counties of a State. Further subsampling could be done in the same manner using townships or sections of land. A frame would be constructed only for the specific areas selected for sampling. Cluster sampling in environmental radionuclide surveys is obvious if large areas are to be sampled.

B. Stratification to Increase Precision

Greater efficiency results from stratification of a heterogeneous population into more homogeneous strata, but increased efficiency in estimating the population average may not justify the added complications. Harris and Tabor(13) have analyzed the situation for weekdays and weekends in air sampling.

An equation can be written to compare the standard error of the average obtained by simple random sampling to stratified random sampling.

$\bar{\bar{X}}$ = concentration average for all strata

Let: $\bar{X}_1$ = concentration average for first stratum (weekdays)

$\bar{X}_2$ = concentration average for second stratum (weekdays)

k = $\bar{X}_1/\bar{X}_2$ or ratio of $\bar{X}_1$ to $\bar{X}_2$

s^2_c = common estimate of variance when about equal in both strata

n_1 = relative number of samples for first stratum

n_2 = relative number of samples for second stratum

n = total of all strata; $n_1 + n_2$

$f_1 = \frac{n_1}{n}$ = fraction of total sample in first stratum = 5/7 for weeks

$f_2 = \frac{n_2}{n}$ = fraction of total sample in second stratum = 2/7 for weekends

$s^2_{\bar{x}_a}$ = estimate of variance of average concentration using simple random sampling

$s^2_{\bar{x}_b}$ = estimate of variance of average concentration using stratified random sampling

$s_{\bar{x}_a}$ = standard error of the average concentration using simple random sampling

$s_{\bar{x}_b}$ = standard error of the average concentration using stratified random sampling

c = coefficient of variation = $\frac{s_{\bar{x}}}{X}$

$R = \frac{s_{\bar{x}_a}}{s_{\bar{x}_b}}$ or ratio of $s_{\bar{x}_a}$ to $s_{\bar{x}_b}$

The equation for estimation of the population's (all strata) average concentration is given by equation (1):

$$\bar{\bar{X}} = \frac{1}{n}\left(n_1\bar{X}_1 + n_2\bar{X}_2\right) \qquad (1)$$

Equation (2) for relative efficiency can be expressed in terms of the standard error:

$$\frac{s_{\bar{x}_a}}{s_{\bar{x}_b}} = R = \sqrt{1 + \frac{f_1 \times f_2\left(\bar{X}_1 - \bar{X}_2\right)^2}{s^2_c}} \qquad (2)$$

As the differences between the averages of the two strata increase, and the relative variance decreases (smaller c), stratified random sampling will produce greater gains in precision. Equation (2) can also be expressed in terms of k and c as in equation (3).

$$R = \sqrt{1 + \frac{n_1 \times n_2\left(k - 1\right)^2}{c^2\left(n_1 k + n_2\right)^2}} \qquad (3)$$

Equation (3) solves an example problem. In general terms, the weekday average is 50 percent higher than the weekend average; the coefficient of variation equals 80 percent; and the number of sampling units are proportioned according to the relative number of days in each stratum, that is, 5 to 2. So, k equals 1.5, c equals 0.8; n_1 equals 5; and n_2 equals 2.

$$R = \sqrt{1 + \frac{5 \times 2\left(1.5 - 1\right)^2}{(0.8)\ \left[5\ (1.5) + 2\right]^2}}$$

$$R = \sqrt{1 + \frac{10\left(0.5\right)^2}{\left(0.8\right)^2\ \left(9.5\right)^2}}$$

$$R = \sqrt{1 + \frac{2.5}{57.76}} = \sqrt{1 + 0.043}$$

$$R = \sqrt{1.043} = 1.022$$

The gain in precision from stratification would be 2.2 percent. Table 1 lists the gains in precision for several combinations of this type of stratification.

Although the differences between strata concentration levels may be significant statistically, the decision to stratify must be based on whether the combination of the ratio of concentrations (k) and the coefficient of variation (c) result in a significant gain in efficiency.

The simple stratification discussed here is only one of many possibilities. Statistical texts(7,8) or a statistician should be consulted on the most efficient means of stratification and the proper statistical estimation techniques.

TABLE 1.--Precision Gains from Stratification

k	c	Percent precision increase
1.5	0.8	2.2%
3	0.8	10.0%
10	0.8	21.2%
1.5	0.25	20.1%
3	0.25	79.0%
10	0.25	140.0%

C. Selection of Sampling Stations

Sampling stations to represent an area may be chosen randomly or by judgment. The general discussion on random vs. nonrandom sampling applies here.

1. Nonrandom Selection

Where only a limited number of sampling units can be used, nonrandom selection of sampling stations may be more representative. One factor which favors judgment sampling is the availability of trained people for sample collection in conjunction with other related programs. Agricultural experiment stations are generally situated to be representative of a given geographical area and have trained personnel available for collection of sampling units. In selecting judgment sampling stations, the factors which affect the transport of the subject radionuclide through the food chain must be considered. Judgment sampling must be well thought out and justifiable. Sampling station selection merely for convenience is not acceptable.

If there are only a few stations through which most of the product being surveyed is processed, they form a natural point of sampling. Examples would include grain elevators, area produce depots, or processing factories. Here representative sampling is simplified to the problems of bulk sampling as all sampling stations are used.

2. Random Selection

Random selection of sampling stations may be accomplished by simple random sampling, stratified random sampling, cluster sampling, or systematic sampling. Simple random sampling may not give the desired precision, especially if there are large differences in radionuclide concentrations between strata. Natural stratification would involve climatic, meteorological, soil-type, and farming practices as examples.

If a listing of all possible sampling stations is not available, cluster sampling can be used. A disadvantage of cluster sampling is that not all strata or areas are represented; so the sampled population may not be representative of the total or target population. The precision achieved by cluster sampling is less than by stratified random sampling, but may be justified.

A second type of stratification required to achieve representative sampling is based on size of sampling station. Those stations with a greater volume of product should either have a greater frequency of selection (to reflect greater effect) or the estimation procedure should be weighted to reflect their great effect.

Random selection of sampling stations may be subject to problems of nonresponse or lack of cooperation on the part of those providing the samples. Serious biases can invalidate the sampling plan if not followed closely. The sampling plan can be designed to minimize these effects. Estimation techniques are available to reduce nonresponse effects to a minimum. This problem may well be of major concern in long-term monitoring surveys.

D. Allocation of Sampling Stations

In stratified random sampling, the sampling stations are apportioned to the various strata. There should be at least two sampling stations per stratum to evaluate variability within strata. Those strata which represent the larger eventual intake to the population and/or those with greater variability should be overrepresented to achieve maximum precision for least effort. Proper procedures must be used to avoid generating a biased estimate of the average concentration value.

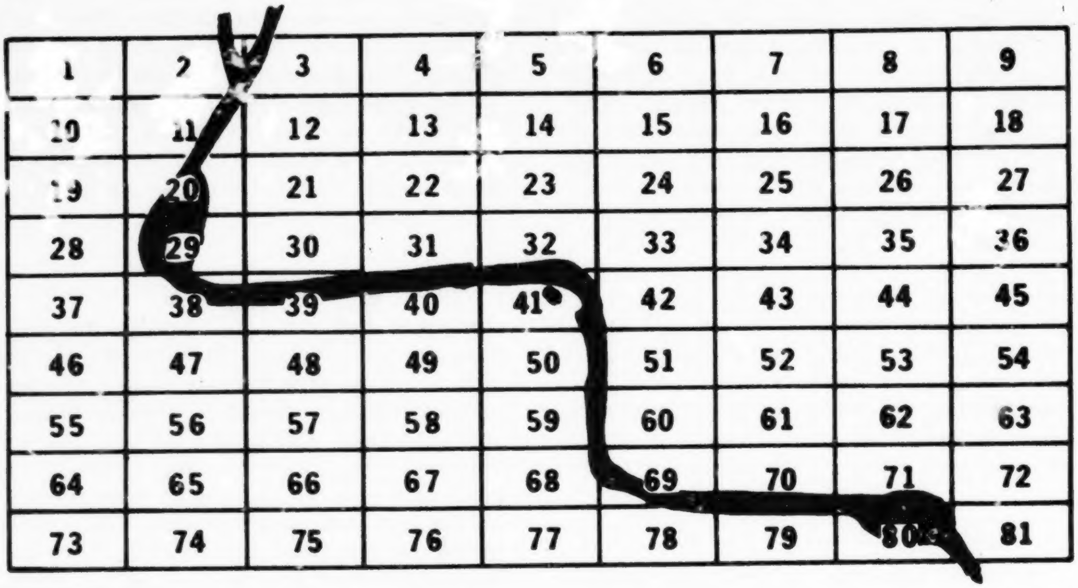
IV. PLOT SAMPLING

Sampling areas can be subdivided by a number of techniques. The area is subdivided by some sort of grid and random sampling is used to select a number of the subareas for actual unit sampling. Some representative examples are discussed.

A. Square Grid Design

A grid overlay could be made for a detailed map of an area and numbers assigned to the subareas. Simple random sampling of a selected number of these areas would provide a statistical sample free of selection bias.

Such a grid is pictured in Figure 1 with the blocks numbered. The grid is a nine by nine grid. Numbered marbles from a jar or a table of random numbers could be used to select the sampling areas. The first column of numbers appearing in the Table of Random Numbers in NBS Handbook #91 is shown in Table 2.(14)



1	2	3	4	5	6	7	8	9
10	11	12	13	14	15	16	17	18
19	20	21	22	23	24	25	26	27
28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45
46	47	48	49	50	51	52	53	54
55	56	57	58	59	60	61	62	63
64	65	66	67	68	69	70	71	72
73	74	75	76	77	78	79	80	81

Figure 1.--Sampling Stations - Square Grid

TABLE 2.--Random Numbers

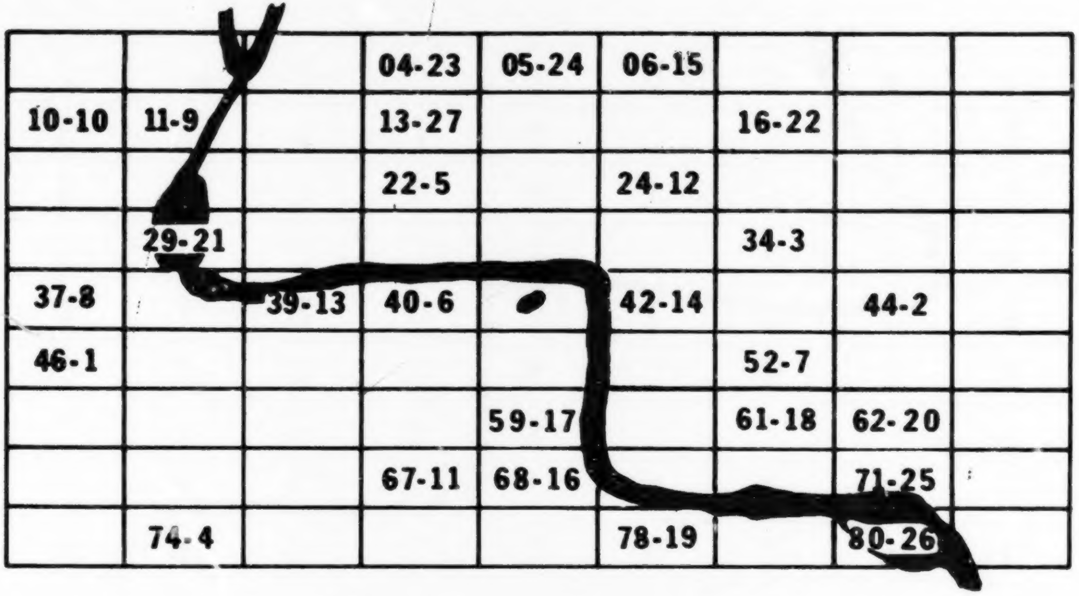
46	44	34	74	22	40	52	37	11	10
67	93	24	39	74	91	42	06	92	91
68	59	39	67	61	78	93	37	62	29
16	04	95	86	59	05	71	80	13	67
72	28	69	71	89	58	50	49	11	34

One could choose the areas so none would be sampled more than once. The first 27 numbers would then designate the areas to be sampled. This selection is shown in Table 3.

TABLE 3.--Selected Random Numbers from Table 2

46	44	34	74	22	40	52	37	11	10
67	~~93~~	24	39	~~74~~	~~91~~	42	06	~~92~~	~~91~~
68	59	~~39~~	~~67~~	61	78	~~93~~	~~37~~	62	29
16	04	~~95~~	~~86~~	~~59~~	05	71	80	13	~~67~~
~~72~~	~~28~~	~~69~~	~~71~~	~~89~~	~~58~~	~~50~~	~~49~~	~~11~~	~~34~~

The areas of Figure 1 selected for sampling are shown in Figure 2 with the second number being the order of selection. The 27 randomly selected areas pretty well cover the area. If one were to use just



			04-23	05-24	06-15			
10-10	11-9		13-27			16-22		
			22-5		24-12			
	29-21					34-3		
37-8		39-13	40-6		42-14		44-2	
46-1						52-7		
				59-17		61-18	62-20	
			67-11	68-16			71-25	
	74-4				78-19		80-26	

Figure 2.--Selected Sampling Stations - Square Grid

the first nine (a sample free of selection bias) one might have qualms about its representativeness. Another approach to the square grid design is through the Latin Square. The first nine letters of the alphabet (A-I) designate the subareas of each row of the grid. Each letter must appear once and only once in each column of the grid. One nine by nine Latin Square by Youden is shown in Table 4.(15)

TABLE 4.--A 9 × 9 Latin Square

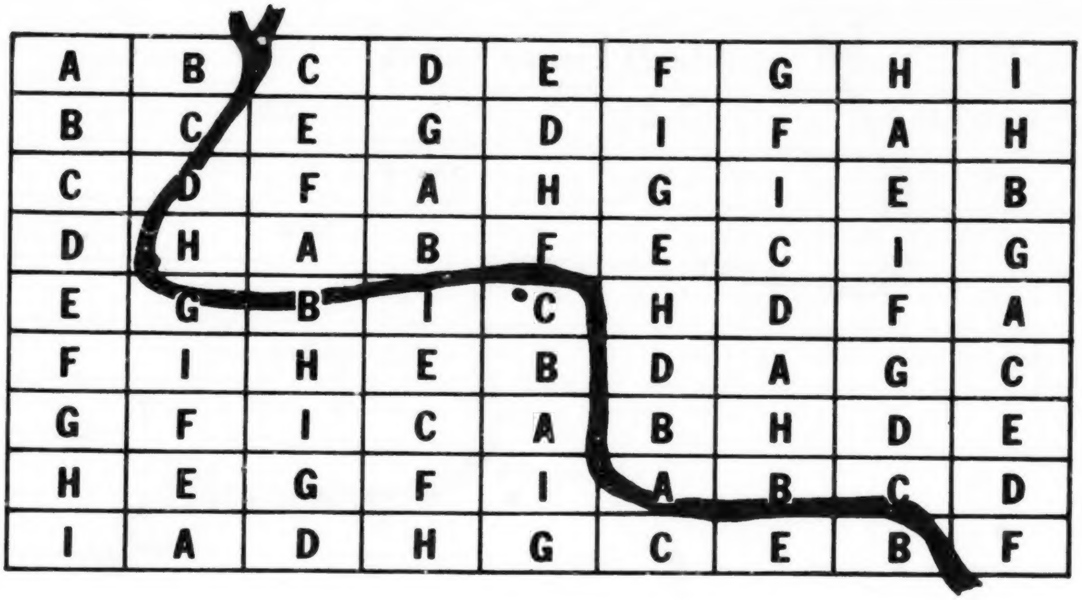
A	B	C	D	E	F	G	H	I
B	C	E	G	D	I	F	A	H
C	D	F	A	H	G	I	E	B
D	H	A	B	F	E	C	I	G
E	G	B	I	C	H	D	F	A
F	I	H	E	B	D	A	G	C
G	F	I	C	A	B	H	D	E
H	E	G	F	I	A	B	C	D
I	A	D	H	G	C	E	B	F

Figure 3 is the same grid as Figure 1 with the subareas designated according to the Latin Square of Table 4.

Using the Latin Square Method, a letter is picked by random process and all subareas bearing that designation would comprise the sample. By looking at the subareas designated by any single letter, each row and column will be sampled only once. A square could be formed of any size. One could, however, choose a second letter and a third if desired. Youden recommends the square be one-half, one-third or some other fraction of the total number of sampling stations. In the example, the nine by nine would be one-third the 27 samples chosen by simple random sampling.

One could choose three letters and collect the samples. The samples from the first two letters could be analyzed first and if the precision is adequate, the third set of samples would not have to be analyzed. This might reduce the total survey costs significantly.

The specific subarea designation should be kept when selecting the samples, using



A	B	C	D	E	F	G	H	I
B	C	E	G	D	I	F	A	H
C	D	F	A	H	G	I	E	B
D	H	A	B	F	E	C	I	G
E	G	B	I	C	H	D	F	A
F	I	H	E	B	D	A	G	C
G	F	I	C	A	B	H	D	E
H	E	G	F	I	A	B	C	D
I	A	D	H	G	C	E	B	F

Figure 3.--Sampling Stations - Latin Square

the Latin Square selection technique for statistical analysis like north half vs. south half, etc. For the letter A in Figure 3 the specific subareas included in this sample are: 1, 17, 22, 30, 45, 52, 59, 69 and 74.

B. Annuli and Sectors Design

The square grid design illustrated is just one example of plot sampling. Another technique that has been used for a plant environs survey utilizes annuli and sectors. The CANEL (Connecticut Aircraft Nuclear Engine Laboratory)[1] monitoring program uses such a design.(16) The circles define the annuli $\frac{1}{4}$, $\frac{1}{2}$, 1, 2, 3, 4 and 5 miles in radius. The annuli are numbered from 1 to 7 working outwards. The annuli are divided into directional sectors; that is, northerly, westerly, southerly, and easterly and denoted by a second number 1, 2, 3, 4, in the above order.

The annuli and sectors can be defined arbitrarily or based on area windroses and natural geographical stratification. Lack of sector symmetry presents no problems.

The CANEL program requires a sample from each of the designated sectors, a total of twenty-eight. Such a grid for the same area as Figure 1 is depicted in Figure 4.

Considerable area is involved in each sector and further subdivision is necessary. For the CANEL program, each sector was divided into nine subsectors. Homogeneity of sectors was ascertained, so one subsector in each sector was chosen by simple random sampling. Any random process could be used to choose the subsector.

The first seven numbers between one and nine in the fourth row of Table 2 could select the subsectors for the easterly quarter. These numbers for the seven annuli of the eastern quarter would be: 6, 7, 9, 3, 2, 4, and 3. The specific subsectors to be sampled would be: 1.4.6; 2.4.7; 3.4.9; 4.4.3; 5.4.2; 6.4.4; and 7.4.3. See Figure 5.

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[1] Pratt & Whitney Aircraft, Division of United Aircraft Corporation, Connecticut Operations-Canel, Middletown, Connecticut.

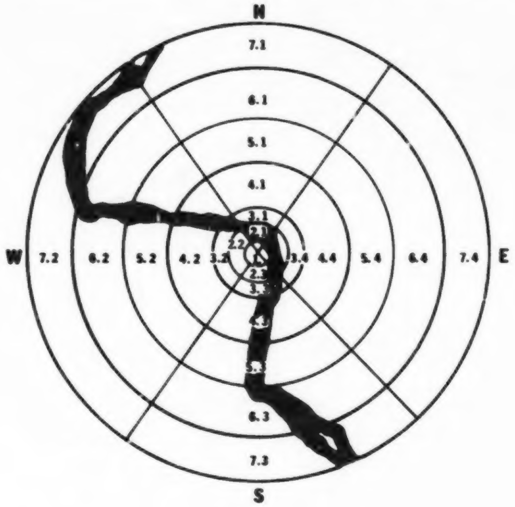

Figure 4.--Sampling Stations - Annuli and Sector Design

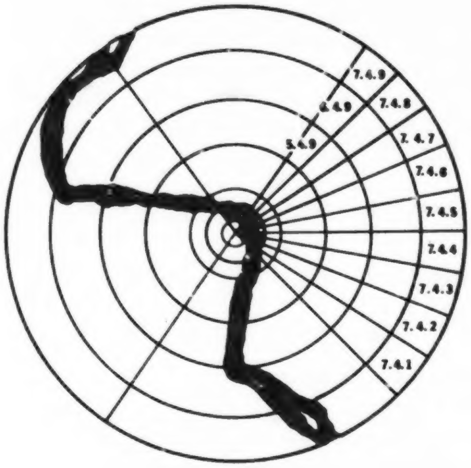

Figure 5.--Subsector Sampling Stations - Annuli and Sectors Design

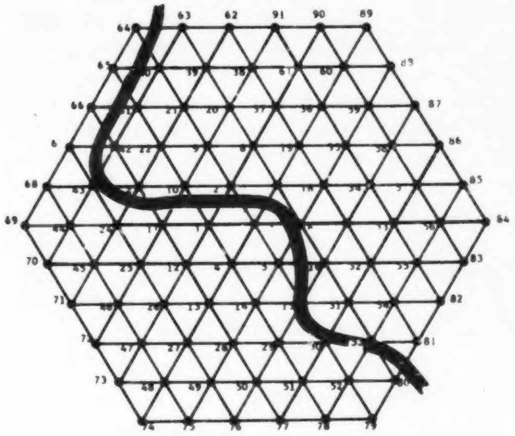

Figure 6.--Sampling Stations - Triangular Grid

C. Triangular Grid Design

The Division of Air Pollution of the PHS in its Nashville Study used an equilateral triangle grid pattern to locate its sampling stations.(17) The stations were located as close as possible to the intersections of the triangular grid where the stations were 0.87 miles apart. This spacing gave a density of about two stations per square mile. Such a grid is shown in Figure 6.

The sampling stations for the survey can be picked by random or judgment. The two judgment subnetworks evaluated in the Nashville study consisted of 32 and seven stations out of the total of 119 in the entire network. Randomly selected subnetworks of 45 and 32 stations were also evaluated. For the pollutants measured--dustfall and lead peroxide sulfation rates--uniform spacing of stations became more important as the number of stations decreased.

The grid designs illustrated are just a few of the many possible. Simple random selection is adequate if sufficient numbers of samples are involved. A few samples selected by the Latin Square, judgment, or equidistant spacing may provide a more representative picture than simple random sampling.

V. AREA HETEROGENEITY

The homogeneity or heterogeneity of an area should be determined in evaluating a sampling design. The selection of a single subsector to represent the sector as practiced in the CANEL surveys was justified because it had been determined that each sector was relatively homogeneous. Such an evaluation also provides information for selection of a stratification scheme based on actual differences in radionuclide concentrations.

A number of techniques are available for evaluation of heterogeneity. These can be applied to variations along a line of physical distance or along a line of time.

A. Youden Sampling Plan

Youden used one technique to assess variability in pH of a particular soil type.(15) He took two samples ten feet apart (#1, 2). From the midpoint of the line joining those two sampling spots, a distance of 100 feet was measured off. The selection of the direction was done randomly. Another set of two samples (#3, 4) was taken. From the midpoint of the line joining the two sets of samples, a distance of 1000 feet was measured off again in a random direction. Four more samples (#5, 6, 7, 8) were taken at that end of the 1000 feet in the same way as at the other end. A total of eight samples then were involved. Such a scheme is shown in Figure 7.

The sampling plan was repeated at distances of one to three miles for the total area being surveyed. For the particular survey involved, increased heterogeneity with distance was clearly indicated. Table 5 (Table 1 of Youden's article)(15) summarizes the discovered differences.

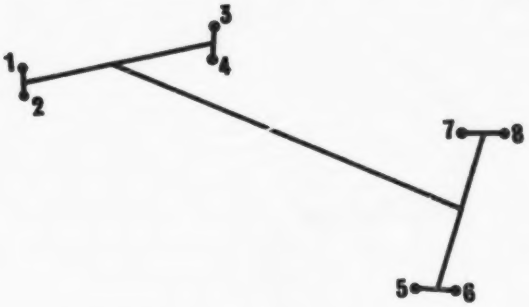

Figure 7.--Sampling Plan - Youden

B. Paired Samples

Another way to assess homogeneity along a line is with pairs of samples. Table 6 gives the organization of the samples.

The results from each pair of samples are added to give a sum "a" and are subtracted to give a difference "d." When there is no trend the "a's" and the "d's" have the same variance. The "a's" will vary more among themselves when a trend is present. The calculations involved are:

1. Calculate Σd^2

2. Calculate $\Sigma a^2 - \frac{(\Sigma a)^2}{n}$ or $\sum\left[(a - \bar{a})^2\right]$

TABLE 5.--Difference in pH of Duplicate Samples of Culvers Gravelly Site Loam

Distance between duplicate samples	0 - 2 inch layer		2 - 6 inch layer	
	Avg. diff.	Max. diff.	Avg. diff.	Max. diff.
10 feet	0.14	0.44	0.11	0.49
100 feet	0.18	0.84	0.20	0.53
1000 feet	0.26	0.69	0.25	0.81
1 - 3 miles	0.36	1.32	0.28	1.05

TABLE 6.--Paired Samples Along a Line

Pair	1	2	3	4---n
	..	..	..	..---..

3. Divide Σd^2 by n = quotient D.

4. Divide $\Sigma a^2 - \frac{(\Sigma a)^2}{n}$ by n = quotient A.

5. Ratio of variance F = A/D is evaluated from the standard tables for "Percentiles of the F" distribution as in NBS Handbook #91, Table A-5 ff. Where the degrees of freedom for the numerator equals n - 1 and the degrees of freedom for the denominator equals n.

6. Large values of the ratio F = A/D indicate heterogeneity.

C. Mean Square Successive Difference Test

This test can be used along either a line or time series and utilizes a sequence of single samples. The samples are arranged in order as in Table 7.

TABLE 7.--Mean Square Successive Differences Test

Sample	Sample value	Successive difference
1	X_1	$d_1 = X_1 - X_2$
2	X_2	$d_2 = X_2 - X_3$
3	X_3	$d_3 = X_3 - X_4$
4	X_4	$d_4 = X_4 - X_5$
.	.	.
.	.	.
n - 1	X_{n-1}	$d_{n-1} = X_{n-1} - n$
n	X_n	--------

The variance, s^2, of the set of measurements is computed in the normal manner. The mean square successive difference, $D^2 = \frac{(\Sigma d^2)}{n-1}$, provides little variation due to trends. But s^2, the variance using $\overline{X}$, shows the presence of a trend by having a large value. The ratio D^2/s^2 should be about (2) if no trend is present. A trend will lower the value of the ratio. If excessively rapid oscillations are occurring both, s^2 and D^2 will be increased (18) with D^2 increasing faster than s^2.

The mean square successive difference, (18) (D^2) can be used to estimate the variance of the population, σ^2, since random samples from a normal population yield a $D^2 = 2\sigma^2$.

If long term trends are present, D^2 may give a better estimate of the basic variance σ^2 than s^2, which can be considerably influenced by the underlying trend and thereby become biased. The mean square successive difference might be used for cyclical or seasonal type data. data.

Table 8, excerpted from Bennett and Franklin, gives limiting values at the five percent and one percent levels of significance. (18)

TABLE 8.--Limits for the Ratio D^2/s^2

Sample size, n	5%		1%	
	Lower	Upper	Lower	Upper
4	0.78	3.22	0.63	3.37
6	0.89	3.11	0.56	3.44
8	0.98	3.02	0.66	3.34
10	1.06	2.94	0.75	3.25
12	1.13	2.87	0.83	3.17
15	1.21	2.79	0.92	3.08
20	1.30	2.70	1.04	2.96
25	1.37	2.63	1.13	2.87

A series of measurements from an assumed random process are analyzed in Table 9, using the mean square successive difference, D^2, technique.

The calculation of s^2 is given in Table 10.

The ratio of D^2/s^2 would equal 365/138 or 2.64. The only conclusion is that the population being sampled appears normal in nature and without detectable trends.

D. Tests for Population Non-Normality

So far the population has been assumed normal in nature. The estimation formulas for variance based on normal populations have been used without a qualification. Although many experimental situations have been shown to at least approximate a normal distribution, others have not. The Nashville study showed that particulate concentrations tend to be log-normally distributed, that is, the concentration values are skewed on the side of high values.(19) Radioactivity surveys have shown normal and log-normal distributions and other distributions not readily characterized.(20)

Populations can be checked for non-normality by plotting the sample data on probability paper. An approximately straight line would indicate a normally distributed population. The Chi-Square test can also be used to check normality of data.

A fundamental property of sampling is that for four or more sampling units of the population, the distribution of means is approximately normal.

The normality of the $\overline{X}$ distribution holds for samples from non-normal populations. This permits estimation of the population mean and standard deviation of the mean using normal population formulas.

TABLE 9.--Calculation of D^2

Sample	Sample value	Successive difference (d)	d^2
1	197	$d_1 = 197 - 200 = 3$	9
2	200	$d_2 = 200 - 223 = 23$	529
3	223	$d_3 = 223 - 186 = 37$	1369
4	186	$d_4 = 186 - 211 = 25$	625
5	211	$d_5 = 211 - 219 = 8$	64
6	219	$d_6 = 219 - 211 = 8$	64
7	211	$d_7 = 211 - 196 = 15$	225
8	196	$d_8 = 196 - 195 = 1$	1
9	195	$d_9 = 195 - 209 = 14$	196
10	209		3282

$$D^2 = \frac{\sum d^2}{n - 1} = 3282/9 = 365$$

TABLE 10.--Calculation of s^2

Sample	Sample value (X_i)	$(X_i - \bar{X})$	$(X_i - \bar{X}^2)$
1	197	8	64
2	200	5	25
3	223	18	324
4	186	19	361
5	211	6	36
6	219	14	196
7	211	6	36
8	196	9	81
9	195	10	100
10	209	4	16
	2047		1239

$$\bar{X} = 205 \qquad s^2 = \frac{\sum (X_i - \bar{X})^2}{n - 1} = 138$$

Only when the population has been demonstrated to be normal or certain restrictions in the estimates have been made, can the formulas for sampling a normal population be applied. If only small-sized statistical samples are involved, the normal distribution does not apply. The "Students" t distribution is more exact.(21) When statistical sample sizes exceed about 30, the normal distribution applies.

VI. COMPOSITES AND ALIQUOTS

A. Composite Samples

If the survey is designed to estimate average radionuclide concentrations over a period of time, compositing of sampling units may produce more representative values. Since radiochemical analyses are relatively expensive, compositing of sampling units from an area or stratum may reduce the survey cost or allow more intensive sampling with the same number of analyses. When sampling units from a number of sampling stations (or from the same station over a period of time) are composited, most information on variability will be lost.

In some surveys the aliquots from the stations in a stratum are combined into two samples(22) by a random process. Two estimates of the average radionuclide concentration are then available and information on variability is retained.

Where conditions warrant, aliquots of the original sampling units can be kept for individual analysis if the composite value is higher than expected.

B. Aliquots

When only portions of the original sampling unit are taken for analysis, the aliquot must be representative of the total sampling unit. Much work has been done on bulk sampling techniques in various industries. Bicking has compiled a "Bibliography on Sampling of Raw Materials and Products in Bulk."(23)

VII. SELECTION OF RANDOM NUMBERS

All probability sampling techniques require the selection of a random statistical sample. Simple random sampling generally enters into some stage of the sampling procedure.

The methods of selecting a simple random statistical sample can be classed as mechanical devices or use of a "Table of Random Numbers." Any device used must have one characteristic to be truly random: Only chance mechanisms must operate in the selection of the statistical sample. Mechanical devices range from simply tagged marbles in a jar to the most sophisticated devices used in gambling houses. Tables of Random Numbers have been specifically generated and tested for this function.

In order to fully utilize the randomness of a Table of Random Numbers, the starting place and order of taking numbers should be randomized. One technique shown uses the Short Table of Random Numbers in NBS Handbook #91, pages T-82 to T-85. The table consists of four pages of numbers grouped in two's. There are 25 columns and 50 rows per page. After selection of the page, column, and row, (the starting is therefore defined) the direction of reading (up or down, right or left, and in which order) must be decided. If a particular row or column does not have enough numbers, the reentry place in the table must be decided.

Select--arbitrarily--any eight-digit number. (One way to make this selection, which in turn will define the starting point, is to blindly choose any one digit on a page. Decide beforehand which direction to go next--left, right, up, or down--and continue until eight digits have been assembled.)

This number controls the starting point, direction, and order of movement. Movement, order, and direction are defined in Table 11 and illustrated in Table 12. As Table 11 shows, the first digit defines the page, the second and third indicate the column, the fourth and fifth refer to the row. The final three digits determine direction of progress once this starting point has been chosen.

The sixth digit determines the order of the next two digits; i.e., 7, 8 or 8, 7. If the sixth

TABLE 11.--Illustration of Random Start

Random Number (digits rearranged):	4 64 43 4 7 4
First digit defines page:	if 3 or 4, use page 2
Second and third digits define column:	if 14, 39, 64, or 89, use column 14
Fourth and fifth digits define row:	if 43, or 93, use row 43
Sixth digit determines whether to perform operation of seventh or eighth digit first:	if even, use seventh digit; if odd, use eighth digit
Seventh digit determines right or left movement:	if even, go up; if odd, go down
Eighth digit determines right or left movement:	if even, go right; if odd, go left

TABLE 12.--Random Start in Selected Table of Random Numbers

To select:						Whether next or last no. (6th digit)	Movement	
Page (1st digit)		Column (2nd and 3rd digits)		Row (4th and 5th digits)			Up or down (7th digit)	Right or left (8th digit)
If digit is:	Use page:	If digits are:	Use col.:	If digits are:	Use row:	If:		
						Even	Start:	Re-enter:
1 or 2	1	01, 26, 51, 76	1	01, 51	1		Even ↑	Even →
3 or 4	2	02, 27, 52, 77	2	02, 52	2		Odd ↓	Odd ←
5 or 6	3	⋮	⋮	⋮	⋮	Odd		Start:
7 or 8	4	⋮	⋮	⋮	⋮			Even → Odd ←
9 or 0	*	25, 50, 75, 00	25	50, 00	50		Re-enter:	
							Even ↑	
							Odd ↓	

*Make another selection.

digit is even, the seventh digit--which controls vertical direction--is taken next. When the seventh digit is even, go up the column; when odd, go down. When the extreme top or bottom of the column has been reached, proceed to the next column. If direction was upward in the last column, begin at the bottom of the new column, and vice versa. The eighth digit controls horizontal movement: If the digit is even, go to the right. If odd, move to the left. Keep in mind that this progress applies only if the sixth digit is even.

If the sixth digit is odd, skip the seventh digit and progress directly to the eighth digit, which determines horizontal movement: To the left from the starting point if the eighth digit is odd, to the right if it is even. At the extreme left or right of the line of numbers used, return to the seventh digit. And again, go up if the seventh digit is even, down if odd.

Continue in this fashion until the needed number of digits has been acquired.

The random selection in this example is as follows: Start on page 2, the 14th column, and 43rd row. Starting with that number proceed downward in that column. If the column is exhausted, enter the next column to the right and continue proceeding downwards.

Using this procedure, one would continue to the next page or go from the last page to the first to get enough numbers for the sample.

It is evident that randomness is not analogous to convenience or without apparent aim. Randomness is done by prescribed and definite techniques.

VIII. SUMMARY

The problem of representative population sampling entails a considered and justified plan of attack. Representative sampling may be either random in nature or based on judgment. Judgment sampling may be more representative than random when only a few sampling units can be taken. Random sampling is by definition free of selection bias; probability theory provides formulas for estimation of the survey's sampling error.

Stratified random sampling can increase precision of a survey over simple random sampling. Cluster sampling may reduce the survey cost or be helpful if a list of all members of a population is impractical or impossible.

The survey can do an efficient job at minimum cost if proper statistical techniques are applied by the designer himself or in consultation with a statistician.

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Guidelines For Emergency Monitoring

I. INTRODUCTION

By implication, it must be assumed that emergency monitoring operations will often be conducted under conditions wherein the identity of the specific contaminants will be unknown. In many instances, however, the probable source of the contamination will be known and this will offer some indication of the general nature of the contaminants.

Currently, maximum permissible concentrations for radionuclides in milk and other foods are based upon drinking water criteria. According to recommendations of the National Committee on Radiation Protection and Measurements (NCRP),(1) the provisional maximum permissible concentration for occupational exposure to unidentified radionuclides in water (above the natural radioactivity content) is 1000 micromicrocuries per liter, assuming alpha emitters are absent. For general population groups, the limit for unidentified radionuclides in water, $(MPCU)_W$, would be of the order of 10 to 100 micromicrocuries per liter. The same levels, expressed in micromicrocuries per kilogram, may, with caution, be applied to foods.

II. EMERGENCY GUIDELINES FOR GROSS RADIOACTIVITY

Initial measurements for evaluation of an emergency will of necessity be limited to gross radioactivity. Establishment of guidelines for such monitoring involves a number of factors. Some of these are discussed in the following paragraphs:

A. Natural Radioactive Potassium in Foods

Most biological materials contain potassium, a naturally occurring radioactive element. The activity in potassium is due to its K^{40} isotope and amounts to about 850 micromicrocuries per gram of the element as found in nature. Assuming an average concentration of some 2 grams of potassium per kilogram of biological material, the resulting K^{40} radioactivity would range from 1000 to 3000 $\mu\mu c$ per kilogram. It is thus apparent that the natural K^{40} radioactivity in practically all foods will exceed the provisional maximum permissible concentration for long-term occupational exposure to unidentified radionuclides.

B. Radionuclide Spectrum of the Emergency

Reference to the chart "Hazardous Radionuclides in Water" reveals that only four radionuclides, Ra^{226}, Ra^{228}, Pb^{210}, and Sr^{90} have MPC values for occupational exposure less than the natural K^{40} content of foods (i.e., = 2000 $\mu\mu c$/kilogram). If exposures for the general population are taken into consideration, the number of radionuclides with MPC values less than the natural K^{40} content of foods would be approximately doubled. All of these except Sr^{90}, I^{131}, Pb^{210}, and Ac^{227} are naturally occurring alpha emitters.

Generally, these four nuclides will contribute only a minor fraction of the gross radioactivity. In fallout, for example, Sr^{90} is less than 3% of the total activity even for one-year-old mixed fission products, I^{131} is never more than 7%, and neither Pb^{210}

nor Ac^{227} occurs at all. In special cases, as for example at Windscale, the relative abundance of these nuclides may be much higher, but the nature of the operation will usually permit this to be known.

C. Duration of Emergency

Emergency monitoring operations will generally apply to conditions of short duration. Maximum permissible concentrations, as recommended by the NCRP, are based on long-term ingestion. Where the exposure is short, the total integrated dose is correspondingly reduced.

1. To cite a specific example, intake of Sr^{90} at a concentration of 10,000 μμc/liter in drinking water for a period of 3 weeks would result in an initial body burden of 0.1 μc, accompanying bone dose rate of 28 millirems per week, and a resulting 60 year dose of about 24 rems (assuming a daily intake of 22,000 μμc for 21 days, 21% of which reaches the bone, and remains there with an effective half-life of 6400 days).(2)

2. If a radionuclide with an effective half-life of 10 days is ingested for 3 weeks at 10 times its MPC, then:

Maximum Body Burden = 7.7 times Maximum Permissible, declining to the Maximum Permissible Body Burden in 30 days;

Maximum Dose Rate = 7.7 times Maximum Permissible, declining to the Maximum Permissible Dose Rate in 30 days; and

Total Integrated Dose = 3 times the permissible 13 week dose.

D. Suggested Guidelines

From the above discussions, the following conclusion may be drawn:

1. The guideline for acceptability must of necessity be well above the natural radioactivity from K^{40}.

2. It may be tentatively assumed that the more hazardous radionuclides ($Sr^{90} + I^{131}$) will not contribute the major part of the gross beta activity.

3. For the short time to which these guidelines are applicable, concentrations well above those permissible for long-term exposure may be accepted.

On this basis, it is suggested that for alpha emitters, a concentration of 100 to 1000 μμc per kilogram serve as a basis for acceptance of foods for consumption during periods of emergency; for beta emitters, a level of 10,000 to 100,000 μμc per kilogram is suggested.

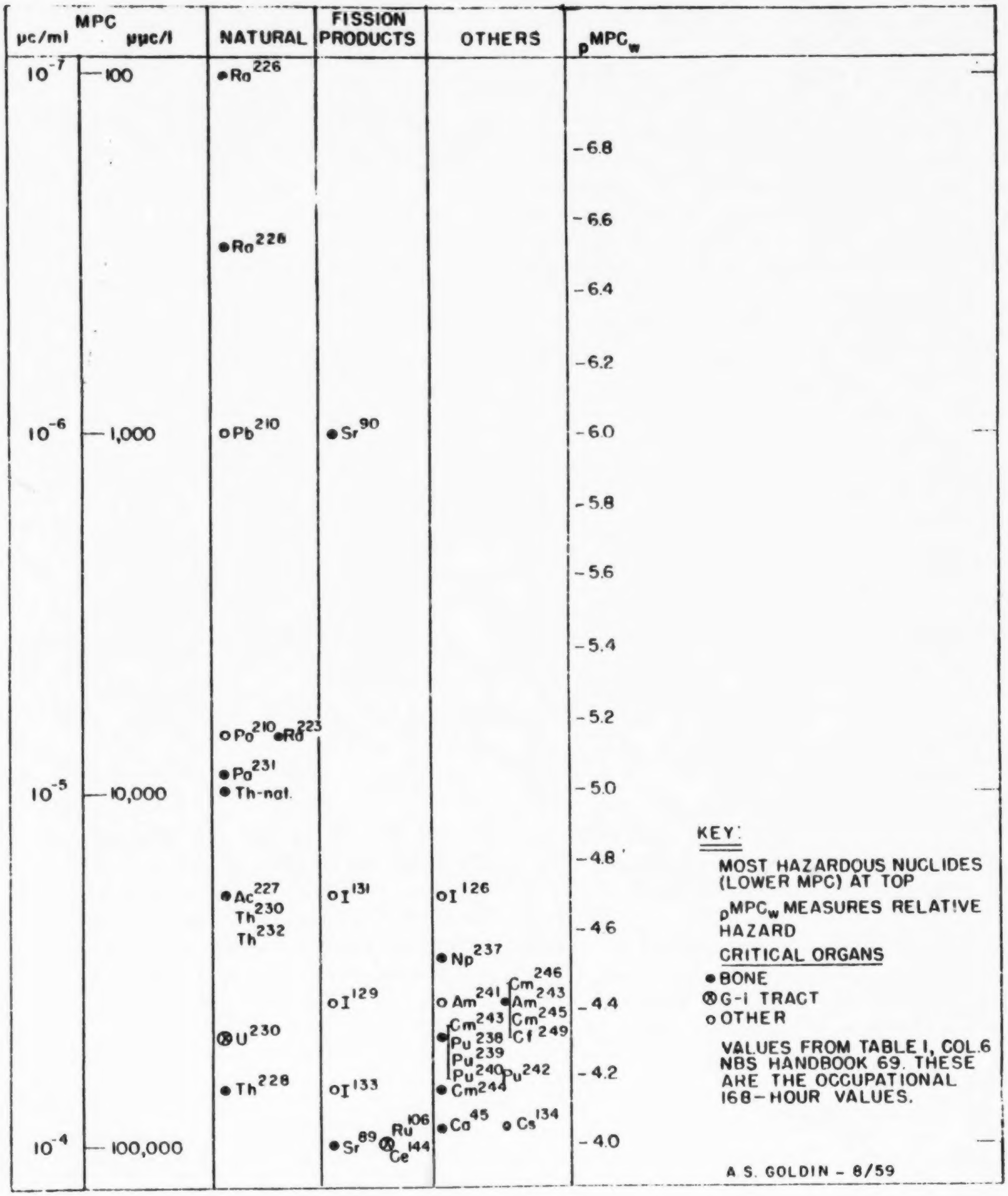
III. EMERGENCY GUIDELINES FOR INDIVIDUAL RADIONUCLIDES

As soon as practical, in any emergency situation, the major radionuclides contributing to the contamination should be identified. This can be accomplished through gamma spectral and decay measurements, and radiochemical determinations of the more hazardous radionuclides, namely Sr^{90} and Ra^{226}.

A. Windscale Experience

Much experience regarding emergency MPC values for individual radionuclides was gained in the reactor accident in England.(3) In October, 1957, a reactor at the Windscale Works, Cumberland, England, went out of control, with a consequent release of a large amount of radioactive material, principally I^{131}, to the general environment. The presence of this nuclide in milk from cows grazing in the area was found to be the major source of potential radiation dosage to the surrounding populace.

HAZARDOUS RADIONUCLIDES IN WATER



I. EMERGENCY MPC VALUES

Milk contaminated by I^{131} from the Windscale Accident was withdrawn from human consumption. Long-term MPC levels did not serve as the basis for such restriction. The following information served as a basis for setting up emergency MPC levels:

a. Medical evidence has indicated that thyroid cancer in children has sometimes followed a radiation dose of 200 rads. The acceptable I^{131} concentration in milk was set therefore, so as to limit the thyroid dose to 20 rads.

b. The dose received by a thyroid, containing 1 μc I^{131} per gram, is 130 rads (at infinity). Assuming a weight of 5 grams for the thyroid in a child, 1 μc I^{131} deposited therein would yield an absorbed dose of 26 rads. Assuming 45% retention in the thyroid, an 8 day half-life, and a milk consumption of 1 liter per day, the emergency maximum permissible concentration for I^{131} in milk would be 0.15 μc per liter.

c. Alternative figures for the mass of the thyroid and percent retention resulted in a calculated concentration of 0.1 μc (100,000 $\mu\mu$c) per liter. This was the value used and may be compared to the occupational MPC of 60,000 $\mu\mu$c per liter in effect in Great Britain.

d. It should be emphasized that such levels cannot be arbitrarily established in advance. It is necessary in each case to balance the risks against the needs.

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Supplemental Notes for Lecture
'Guidelines for Emergency Monitoring of Foods'

By Dr. E. L. Saenger

PROCEDURES FOR PURIFICATION OF WATER AND FOOD

It is possible that there could be a severe radiation accident with widespread contamination of water supplies, crops and farm animals over a rather large area. The Windscale accident in Great Britain was such an incident following which there was contamination of milk by various radioisotopes, principally I-131. In such a situation, steps must be taken to protect the surrounding population from ingestion of these hazardous substances. Although such measures are not the prime responsibility of the physician in charge of the accident, his role will require immediate notification of health authorities so that the necessary precautions can be taken and techniques disseminated to the general population for adequate care in this situation.

I. CONTAMINATION OF LARGE AREAS

The possible routes leading to contamination of foods, water and food producing areas have been described in sections III and IV. Contamination of animals, plants, ground, water and sewage is discussed in section IV.

II. WATER

Water is essential to maintenance of life and also required for many purposes after any disaster. Public panic in the event of actual or suspected radioactive contamination of water will be a definite problem and instructions for the public should be provided.

Public water supplies can become contaminated by sabotage or by fallout from reactor accidents or direct contamination from radionuclides from other accidents. Detection of gross contamination from beta-gamma activity can be done with portable Geiger-Mueller counters. Samples can be assayed more accurately in many radioisotope laboratories in hospitals or industrial plants.

If community water supplies are seriously or completely disrupted, it then becomes necessary to use water which may be contaminated for drinking purposes. Table I gives emergency levels for food and water immediately following a nuclear explosion. In a situation of utmost gravity, such limits would have to be utilized. If uncontaminated or less contaminated water is available even at a distance, such water should be used.

For emergency purposes, water can be monitored and assayed for beta-gamma activity by use of survey type Geiger-Mueller counters and suitable standards. Such standards are available in Civil Defense centers and it is only necessary to have the water in a container of dimensions similar to that of the standard. Only by use of the standard can the activity be expressed in microcuries or disintegrations per minute as in Table I.

It is possible to assay for gross alpha activity if suitable alpha detectors are available. Such detectors can detect alpha activity in the presence of beta-gamma activity.

If such emergency measures for water are required, immediately after a serious radiation accident, the contribution of alpha activity during the first 10 days will be of relatively little significance as compared to beta-gamma activity. This situation follows because of the presence of many short-lived fission products. After 10-30 days, alpha activity is more important because the short-lived fission products have decayed.

In accidents involving fissionable materials, Table I permits higher values within 10 days than at 30 days since most radioactivity within the first 10 days is due to short-lived radionuclides. Persistent alpha contaminants which are usually long-lived become more important hazards after 10 days as do long-lived beta-gamma emitters. Most peacetime accidents should be well controlled by this time.

Removal of radioactive materials from water is involved and uncertain. Conventional treatment processes are not completely effective in removing all possible contaminants. The removal of any chemical substance, radioactive or not, is dependent upon its physical and chemical nature. A common radioactive characteristic does not imply a common removal tendency when subjected to the various treatment processes. If radioactive materials were to be deposited in a stream or watershed, several natural agencies would be effective in reducing the amount which might finally reach the treatment plant. Among these agencies, the most significant are:

1. Natural decay which is continuous, unaffected by the chemical or physical state of the isotope, and in most fission products quite rapid, decreasing with time.

2. Dilution of the radioactive materials with the water reducing the concentration significantly.

3. Adsorption of the radioactive substances on suspended turbidity particles or other matter with subsequent sedimentation, and adsorption on bottoms and banks of streams and reservoirs.

Research is under way to determine the efficiency of the several conventional water treatment processes in removing radioactive isotopes. The procedures that can be employed by a rapid sand filter plant to improve its efficiency for removing radioactive substances are:

1. Increased dosage of coagulant to produce most effective floc formation.

2. Maintenance of the pH of coagulation as high as possible (a pH of 10 or 11 being preferable) by the addition of excess lime or soda ash.

3. Addition of coagulant aids such as activated silica, bentonite or other clays, and activated carbon.

The general function of these steps is to improve coagulation and thus increase adsorption by agglomeration. Whether or not safe water is produced will depend upon initial concentration of contaminants in the water, their susceptibility to removal, and the efficiency of the treatment processes. In any event, the finished water should be assayed for radioactivity. If the amount exceeds accepted tolerance limits, it should of course not be used.

III. FOOD

Foods may become contaminated by unfissioned material, fission products or by induced radioactivity from neutron waves. Neutron-induced radioactivity will be of little importance in civilian accidents.

Contamination of food can be of two types. The first is direct contamination of foods which are in groceries, warehouses or homes ready for immediate consumption. The second is contamination of farm land as described in section IV so that the radionuclides will be carried through the ecological cycle of the contaminated area. This latter type is of great long-term importance for public health and may result in large economic losses. Incorporation of radionuclides into foods will not occur for about 10-30 days after the accident.

The contamination of food products may occur as a powder or mist or by penetration of contaminated water through porous containers. Sealed canned foods can be decontaminated by wiping and washing with a detergent. Surface layers of bags, cases or bulk food showing heavy contamination may be removed and impounded to permit decay of radioactive materials. Such supplies should be assayed for types and quantities of radionuclides present. Directly contaminated perishable foods may be cleaned by removal of surface layers and surveyed with suitable detectors. If contaminated foods are to be thrown out, they should be sealed in heavy plastic bags or drums and clearly labeled. They should not be placed in the usual garbage disposal systems.

Table II describes some useful techniques for salvaging various types of foods under emergency conditions.

At times, insecticides and other poisons are stored in the same warehouses as are foodstuffs. In the event of fire or explosion, foods may become contaminated by these agents as well as by radioactivity.

IV. CONTAMINATION OF FARM LANDS

Fallout and rainout of radionuclides following a major reactor accident may result in serious contamination of large areas of the countryside. Evacuation of people could be required for long periods of time.

Table I

Suggested emergency levels for food and water immediately following a nuclear explosion

Consumption Period	Beta Activity Levels		Alpha Activity Levels	
	Microcuries per cc	Disintegrations per min per cc	Microcuries per cc	Disintegrations per min per cc
Preferable Risk				
10 days	3.5×10^{-3}	7.7×10^{3}	2×10^{-4}	440
30 days	1.1×10^{-3}	2.6×10^{3}	6.7×10^{-5}	145
Acceptable Risk				
10 days	9×10^{-2}	2×10^{5}	5×10^{-3}	1.1×10^{4}
30 days	3×10^{-2}	7×10^{4}	1.7×10^{-3}	3.7×10^{3}

Table II

Salvage of typical foods

Kinds of foods and of packages	Possible salvage procedure in case of -		
	Contamination with radioactivity	Blast and fire damage	Water damage (pollution)
Perishable: Fresh fruits & vegetables, fish, poultry.	Remove outside portions of lot containing most radioactivity. If remaining contamination is less than emergency tolerance, release interior portions. Washing of fruits and vegetables may be of value.	Look for contamination with poisons. If pathogens are present, sterilize before using.	Wash to remove surface contamination. Cook to kill bacteria.
Nonperishable: Dried fruits & vegetables, flour and grains, bulk sugar stocks.	Remove outside portions of lot containing most radioactivity. If remaining contamination is less than emergency tolerance, release interior portions. Washing of fruits and vegetables is not feasible.	Look for contamination with poisons. If pathogens are present, sterilize before using.	Prompt sterilization and use of fruits and vegetables. Remove flour and grain which is not caked. Cook before using. Refine sugar.
Cardboard and paper containers.	Remove outside portions of lot containing most radioactivity. If remaining contamination is less than emergency tolerance, release interior portions. Remove dust by brushing. Remove outer wrappers.	Look for contamination with poisons. If pathogens are present, sterilize before using.	If salvage attempted, sterilize food from water-damaged container before it is consumed.
Canned goods: Hermetically sealed cans.	Wash outside of container with detergent, or remove radioactivity by brushing. Interior portions of stacks may be relatively free of radioactivity.	Look for and destroy cans with ruptured seams or closures. Remove abnormal cans. Look for spoilage from thermophilic organisms.	Sterilize surfaces of cans. Watch for pinholing of metal. Use damaged stocks promptly.

Table II

Salvage of typical foods--Continued

Kinds of foods and of packages	Possible salvage procedure in case of -		
	Contamination with radioactivity	Blast and fire damage	Water damage (pollution)
Containers with screw caps, friction type lids, etc.	Wash outside of container with detergent, or remove radioactivity by brushing. Interior portions of stacks may be relatively free of radioactivity. Test contents before releasing for use.	Look for and destroy cans with ruptured seams or closures. Remove abnormal cans. Look for spoilage from thermophilic organisms.	Difficult to remove contamination from beneath or around closure. Sterilize foods before using.

Radioisotopes Distributed by Oak Ridge National Laboratories in Curies

	1959	1946-59
Carbon-14	16	85
Cesium-137	76,037	93,239
Cobalt-60	168,817	678,565
Iodine-131	649	6,590
Phosphorus-32	163	1,656
Hydrogen-3	40,902	92,900
Krypton-85	3,107	6,635
Strontium-90	122	561
Promethium-147	567	1,270
Iridium-192	8,666	30,863
All other	319	1,541
TOTAL	299,365	913,905

Report on Emergency Exposure to External Radiation

(Recommendations of the M.R.C. Committee on Protection Against Ionizing Radiations)

I. GENERAL

The Medical Research Council has continued a study of the effects on the health of persons in the neighbourhood of atomic energy installations should there be a release of radioactive material as a result of fires or other incidents. The Council's Committee on Protection against Ionizing Radiations has already reported (Medical Research Council, 1959) on the maximum permissible dietary contamination for iodine-131, strontium-89, strontium-90 and caesium-137, since it was considered that for the members of the public normally resident in the area affected "ingestion of contaminated food would generally be the limiting source of hazard after any such accident" and that "intake by inhalation, or radiation from the exterior, would become of importance only in rather special circumstances".

The present report deals with the problem of exposure from the exterior, namely, from external sources of beta and gamma radiation. This exposure might be derived from two sources, one of relatively short duration from the passage of a cloud of radioactive material, the other of longer duration from deposited material. It is necessary to consider what the biological consequences of such exposure might be, so that appropriate administrative actions can be planned. For instance, it would be possible, in spite of all the difficulties, to evacuate people temporarily to spare them the external dose from the contaminated environment. This procedure would, however, necessitate a decision as to when they could return to the area.

The only people who might be at risk are those in the immediate neighbourhood. These people might receive, from a passing cloud, exposure to gamma rays at a relatively high dose-rate, which would depend markedly, among other things, on whether they were indoors or in the open at the time. The doses so received would affect the acceptable amount of radiation they may subsequently be allowed to receive from deposited material.

The relative importance of exposure to the cloud and to the deposited material is dependent upon so many factors, including the nature of the incident itself, that the Council's Protection Committee has felt it appropriate simply to recommend certain total doses that should, if possible, not be exceeded. In deciding upon these doses the Committee has used the fullest information available at the present time, but it should be realized that knowledge of the effects of ionizing radiation is continually increasing and that the subject of permissible doses is constantly under review.

The specification of acceptable levels of exposure to radiation, whether it be for persons occupationally exposed or, as in the present case, for persons exposed as the result of an accident in a neighbouring atomic energy installation, is a complex task in which many factors have to be balanced. It is necessary to take into account both short- and long-term effects, for which, as the dose and dose-rate increase, so in general does the probability of manifestation. Since recovery plays a part, some effects may be merely temporary. Thus, although certain doses are described as acceptable, they do not represent levels below which there is no effect whatsoever and above which there will necessarily be serious consequences. This point is particularly important in relation to exposure occurring in an emergency when the evacuation of people is contemplated. There are hazards in such an operation and if doses somewhat in excess of those considered acceptable appear likely to be received, the responsible authority will have to assess the relative risks of these against those of evacuation.

The acceptable doses should be considered in the light of the previous paragraph. They are such that neither short- nor long-term effects are likely to be observed even if the irradiation were all due to the passage of a radioactive cloud and thus of short duration. There is a possible exception to this, which is discussed in more detail below, namely, the irradiation of the embryo or foetus. In deciding upon the acceptable doses the Committee has taken into consideration that it is possible but unlikely that the same persons would be significantly exposed in more than one emergency, and the levels are such that a second exposure after a period of some years should not give rise to undue concern.

The present proposals may be compared with the most recent Recommendations of the International Commission on Radiological Protection (I.C.R.P., 1959, 1960), but in so doing it should be appreciated that the Commission has not so far dealt with the problem of emergency doses for members of the general population. The I.C.R.P. recommendations refer principally to the long continuing exposure of adults in the group that is occupationally exposed to ionizing radiations, and are intended to limit both the short-term and the long-term effects to acceptable levels. Reference is, however, made to the "accidental" and "emergency" exposure of persons in this group and also to the long continuing irradiation of persons in certain special groups amongst which are "members of the public living in the neighbourhood of controlled areas". The Commission has also suggested a maximum permissible genetic dose for whole populations together with an illustrative apportionment of this dose to various sources of exposure. All these aspects are discussed below in relation to the present proposals.

II. RECOMMENDATIONS

The following total doses of radiation are considered acceptable for members of the general public as a result of an incident at an atomic energy establishment.

They are to be considered as independent of the duration of the irradiation:

A. The dose of gamma rays giving exposure to the whole body but measured in free air:

Children up to the age of 16 years and pregnant women	20 roentgens (r)
Other persons	30 roentgens

(In the circumstances envisaged, 30 r will give rise to about 25 rads in superficial tissues: 20 r will give rise to about 15 rads in superficial tissues and about 10 rads in an embryo or foetus.)

B. Subject to (A) above, the combined dose of beta and gamma rays giving exposure to the whole body surface and estimated in any superficial tissue:

Children under the age of 16 years	75 rads
Other persons	150 rads

C. For small areas of contaminated skin in total not greater than 1/10 of the body surface, doses from beta rays averaged over 1 cm^2 additional to those specified in (B) above:

Children up to the age of 16 years	75 rads
Other persons	150 rads

D. In order to allow essential duties to be performed, a special category of a few persons is envisaged, consisting of adult males (preferably in the older age groups) or of females above reproductive age. For this group, a dose of gamma rays giving exposure to the whole body but measured in free air, additional to the doses specified in (A), (B) and (C) above: 30 roentgens

III. COMMENTS ON THE RECOMMENDATIONS

A. General

The above recommendations refer to doses of radiation that are considered to be acceptable in an emergency for members of the general public. In applying the recommendations, however, the objective should be to minimize exposure as far as is practicable and to avoid exposure that is unnecessary.

B. Dose of gamma rays giving exposure to the whole body

The dose of gamma rays specified in recommendation (A) for adults is about half the maximum dose to age 30 recommended in the last report of the Medical Research Council (1956), for persons occupationally exposed to ionizing radiations. In the current recommendations of the I.C.R.P., the maximum permissible dose to age 30 from occupational exposure is 60 rems*, the rate of dose accumulation averaging 5 rems per year and being limited to 12 rems in a year. The dose specified in recommendation (A) therefore represents 5 years' accumulation at the average permissible rate and approximately 2 years' accumulation at the maximum permissible rate. It is also equal to the "accidental high exposure" dose which is regarded by I.C.R.P. as acceptable "once in a lifetime" by radiation workers without loss of radiation status, and is approximately twice the dose of 12 rems recommended by I.C.R.P. as being the basis upon which emergency operations by radiation workers should be planned. As regards the doses recommended by I.C.R.P. for persons not occupationally exposed, 25 rads represents about 17 years' exposure at the annual rate of 1.5 rems which is permitted without medical supervision to adults who may be irradiated from nearby sources.

The most difficult decision to take was that concerning an acceptable dose for an embryo or foetus. In the first place, the embryo is much more sensitive to the effects of radiation than mature tissue. There is qualitative evidence of this from experience in clinical radiology. There is further evidence of a semi-quantitative nature derived from irradiating pregnant experimental animals. Under these conditions, moderate doses of radiation during the earliest stages of development of the fertilized egg may lead to the death of the embryo; this would probably not be recognizable in the human case. At an intermediate stage when the various tissues are being differentiated, the embryo may not be killed by radiation but be born alive with developmental defects. Doses as low as 25 r to the pregnant mouse have been recorded as producing a significant number of detectable deformities (Russell, 1957). (In the human being this particular stage of morphogenesis may extend from somewhat before to just after the second month of pregnancy; that is, it is at a time when pregnancy may not be suspected or affirmed.) The final stage of foetal life which is short in the mouse (but long in man) is marked by a rapid increase in resistance to this type of damage by radiation.

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*For radiations of the type considered in this report the relative biological effectiveness is 1 and the rem and the rad can be regarded as equivalent.

Secondly, some recent surveys of the histories of children dying before the age of 10 years from malignant disease suggest that prenatal exposure to X-rays could have been a contributory factor. The normal death rate in England and Wales from malignant disease before the age of 10 is of 1 child in every 1,200, and a survey by Stewart et al. (1958) suggests that this rate may be doubled by irradiation in utero arising from the abdominal X-ray examination of the mother. However, a survey being carried out by Court Brown et al. (1960) indicates that, if there is any effect at all, it is much less than that reported by Stewart et al. Studies made in the United States and elsewhere have also shown conflicting results (Kjeldsberg, 1957; McMahon, 1958; Ford et al. 1959).

The various surveys differ in the way in which the study and control populations were selected, and also in the way in which the fact of prenatal diagnostic examination was established. Also it is possible that the mean levels of radiation dose given in the diagnostic examinations were not the same for the different surveys. It is hoped that further investigations will clarify the issues. In the meantime the possibility of effects arising from antenatal radiography must be considered to be sub judice.

However, if we use the finding of Stewart et al., an assessment can be made of the maximum likely effect of a dose of 10 rads to the embryo or foetus. We estimate that the mean foetal dose received during the abdominal X-ray examinations was possibly about 1 rad, although it may have been several times higher in individual cases. The rate of incidence of pregnancy in England and Wales is about 12 per 1,000 persons. Consequently (assuming a linear relationship and that the doubling dose is 1 rad), the number of childhood deaths due to malignancy before the age of 10, induced by a mean dose of 10 rads in utero through the exposure of 1,000 persons could be:

$$12 \times \frac{10}{1} \times \frac{1}{1200} = 0.10$$

If the mean foetal dose had in fact been higher than 1 rad, this result would have been proportionately less.

The I.C.R.P. recommendations do not exclude pregnant women from occupational exposure and consequently, according to the current recommendations, they would be permitted up to 9 rems during the nine months of any one pregnancy. Women of reproductive age are, however, debarred from receiving the dose of up to 12 rems that radiation workers are permitted during planned work in "emergencies" which might arise in certain operations. This exclusion of such women was intended to protect an unsuspected foetus from receiving such a large dose in so short a time.

The dose of 20 r for children up to the age of 16 was chosen as being intermediate between the foetal and adult doses. It is desirable to specify a lower dose than for adults as (i) it is known that children are more radiosensitive, (ii) the mean tissue dose will be higher for a child than for an adult receiving the same superficial dose, and (iii) children have a longer period during which any potential effect could be manifested. Owing to the possible presence of children among persons living in the vicinity of radiation installations, I.C.R.P. limits the maximum whole-body dose for such persons to 0.5 rem per year; accordingly, a child would be permitted 8 rems to age 16.

C. Combined dose of beta and gamma rays giving exposure to the whole body surface and additional dose of beta rays to small areas of skin

Recommendation (B) permits, in the presence of the maximum recommended exposure to gamma rays, beta-ray doses of about 60 rads up to age 16 and 125 rads above age 16. Beta-ray exposure is confined to superficial tissues and the I.C.R.P. recommendations pertaining to the skin are relevant. The current I.C.R.P. recommendation for the skin for persons occupationally exposed is 30 rems per year and thus the combined doses for persons up to and over the age of 16 represent 2 1/2 years' and 5 years' exposure respectively at the maximum permissible rate for radiation workers.

The additional beta-ray doses referred to in recommendation (C) are mainly intended to cover the cases of (a) beta-active dust trapped in flexures of the skin, and (b) the beta-ray exposure of the hands of the category of persons referred to in recommendation (D). In this connection it should be noted that the current I.C.R.P. recommendation for the hands and forearms, feet and ankles for persons occupationally exposed is 75 rems per year.

The lens of the eye is protected to a great extent from beta radiation by its depth (about 3 mm), so that the dose received will be essentially equal to the gamma-ray dose plus a small fraction of the beta-ray dose. It is unlikely that this fraction will exceed 1/10, and it is considered that for the beta-ray energies likely to be encountered, the recommendations will ensure that the dose to the lens will be acceptably low.

D. Additional dose of gamma rays giving exposure to the whole body permitted for essential duties

The type of duty envisaged for the special category referred to in recommendation (D) is the tending of livestock, the maintenance of public utility services, and emergency activities of various types. The number of persons permitted this additional exposure should be small and they will need to be specially supervised. If considerable exposure to beta radiation is envisaged, the wearing of appropriate clothing should be considered and it will of course be necessary to control as far as practicable the hazards from ingestion and inhalation.

E. Genetic Considerations

It is thought that only a few people would be involved in the conditions under consideration and indeed, provided the number were small compared with one-fiftieth of the whole population, no further limitation of the doses would be necessary on genetic grounds. In its apportionment of its suggested whole population genetic dose, I.C.R.P. allocates 1.0 rem to occupational exposure, 0.5 rem to the exposure of certain special groups and 2.0 rems to the exposure of the population at large. The present recommendations for emergency exposure will result in a "genetic dose" per incident which is extremely small compared with 0.5 rem, as the proposed maximum gamma-ray dose per person involved is, in general, 25 rads and it is anticipated that the number involved will be very small compared with one-fiftieth of the population.

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